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Robot Manipulation of Deformables through Dynamic Actions

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Executive Summary

Europe's research and industrial ecosystems have increasingly prioritized **robotic textile manipulation (RTM)** as a strategic domain over the past decade. This deep-dive assessment finds that Europe's current capabilities, socio-economic drivers, and policy frameworks are **only partially aligned** with the evolving technological and industrial needs in RTM. Further coordination and investment are needed to fully capitalize on automation opportunities in the textile and clothing sector. Key findings include:

- **Technological State-of-Art:** Handling soft, deformable materials like textiles remains a formidable challenge for robotics. No commercially dominant solution has yet emerged for fully automating complex garment manufacturing tasks. Many solutions are currently at the prototype stage and have not yet been deployed at scale [38, 66].

- **EU R&D Leadership:** Europe has established itself as a leading region for RTM research through large-scale collaborative projects and networks, like the one that will be established in the ROMANDIC EU project.

- **Socio-Economic Drivers:** Sustainability pressures and supply chain vulnerabilities (highlighted by the COVID-19 pandemic) are pushing Europe to **re-shore** or near-shore textile manufacturing for resilience. Automation is needed to make local production economically viable despite higher wages, while also supporting on-demand manufacturing and waste reduction. Notably, Europe's textile and apparel trade deficit reached €70 billion in 2022 (48% higher than the previous year) as imports from Asia surged [45, 55].

- **Policy Alignment:** EU policy bodies recognize RTM as strategically important, linking it to goals in industrial competitiveness, digital leadership, and sustainability. The EU Commission has updated the *Industrial Strategy*, and promoted initiatives like the *EU Strategy for Sustainable and Circular Textiles* [35] and the *European Partnership for Textiles (2025–2030)* [35]. At the same time, Europe's *Made in Europe* partnership (successor to Factories of the Future) and EFFRA roadmap have kept flexible material handling on the agenda, ensuring RTM remains a funding priority [45]. The implementation is still in early stages.

- **Comparative Positioning:** The United States, faced with similar reshoring imperatives, has leveraged defense-backed consortia (e.g. the Advanced Robotics for Manufacturing (ARM) Institute) to fund focused projects on robotic sewing and fabric handling aimed at re-shoring apparel manufacturing [4, 101]. US startups have developed robotic sewing lines with claimed capability to produce garments at costs comparable to offshore labor [68, 94]. China has made **massive investments in robotics and AI** as part of national strategies (e.g. Made in China 2025), leading to rapid automation gains in many sectors [12]. Several Chinese apparel factories are piloting "dark factories" with fully automated production and minimal human labor [5, 33]. Europe's advantage lies in its coordinated policy support and expertise network, but it risks lagging in commercialization speed and scale unless new lab innovations translate faster to industry deployment.

- **Challenges & Critical Perspectives:** Despite clear momentum, Europe faces critical challenges in aligning RTM capabilities with industrial needs:

Figure 1: Challenges to align RTM capabilities with industrial needs

- **Technical Gaps:** Robots still struggle with the flexibility and variability of textiles. Fabrics can drape, stretch, or change shape unpredictably; hence, ensuring **process reliability** across varying materials remains difficult. Many current solutions work only for narrowly defined materials or products (e.g. a specific garment type or fabric stiffness). Achieving human-level dexterity in general textile manipulation is an unsolved problem. Real-world manufacturing requires **speed** and **accuracy** simultaneously.
- **Data and Evaluation Limitations:** It is difficult to quantify Europe's "RTM readiness" due to sparse data on automation adoption in textile factories. Official robotics statistics do not isolate textile applications. Anecdotal evidence suggests very low uptake of robotics in European apparel manufacturing to date (the few exceptions being pilot lines). Benchmarking progress is also tough. There are no standard performance benchmarks for cloth manipulation; however, in research, some common test tasks and simulators exist [72]. This lack of data hampers policymakers' ability to track impact or confidently set targets for technology deployment.
- **Economic Feasibility:** Some experts question the economic viability of fully automating garment production, especially for low-margin, fast-fashion items. High up-front capital expenditure for robotics, combined with integration complexity, can deter SMEs that dominate Europe's textile industry. While automation lowers long-term labor costs, it introduces new costs: for maintenance, programming, and the skilled engineers required to operate and supervise advanced machinery. Paradoxically, even as RTM addresses worker shortages on the factory floor, it creates demand for robotics and AI specialists, where Europe also faces a skills gap [102].
- **Workforce and Social Considerations:** There is a cautious discourse around

Figure 2: Actionable recommendations to strengthen EU strategic positioning in RTM

automation's impact on jobs. In fact, labor shortages are so acute that robots are mostly filling a gap, not displacing an available workforce in textile production. Companies need to automate, and this creates new opportunities in the whole textile ecosystem. Managing the transition through retraining programs and "living labs" (where workers can upskill alongside new technology) is deemed essential [52].

  - **Diverse Regional Strategies:** Countries with significant textile manufacturing (e.g. Italy, Portugal, Spain) are naturally more invested in these innovations than those that largely offshored production decades ago [40, 42]. Other countries focus in the production of machinery (e.g. Germany), or the recycling industry (e.g. Eastern EU). An EU strategy must focus on the challenge of coordinating the different strategies, highlighting the synergies and opportunities among the different fields, and the opportunity to retain and create new business opportunities.

- **Recommendations:** To strengthen Europe's strategic positioning in RTM, this report proposes a set of forward-looking, actionable recommendations:

  - **Invest in Scale-Up and Demonstrators:** The EU should support **pilot factories** and **innovation hubs** that bridge the "valley of death" between lab prototypes and industrial deployment. The industry needs these real-life proofs of concept to observe and learn, and would help uncover practical issues of systems integration. Funding instruments under Horizon Europe or the new Textile Partnership can be directed to such flagship demonstrators, ideally in partnership with industry consortia.
  - **Strengthen Cross-disciplinary Collaboration:** RTM sits at the intersection of advanced robotics and traditional textile process know-how. European networks should facilitate deeper collaboration between **roboticists, material scientists, and textile engineers**. One direction is to expand the *Network of Excellence approach of ROMANDIC* (which aims to connect top labs and stakeholders in deformable object handling) into a broader European *Alliance for Textile Automation*. Annual challenge competitions (similar to DARPA challenges) focused on tasks like automated garment assembly could spur innovation and attract talent to the field.

- **Support SMEs with Robotics-as-a-Service (RaaS) Models:** Given the limited capital and expertise of many textile SMEs, new business models should be promoted to lower adoption barriers. The EU and EIB (European Investment Bank) could seed specialized providers/startups that offer RaaS in the textile domain, possibly leveraging Europe's existing network of **Digital Innovation Hubs** to connect technology providers with end-users. This approach also ties in with **SME digitalization programs** under the Digital Europe Programme.
- **Upskilling and Training Programs:** To ensure a skilled workforce for automated textile factories, targeted training must be ramped up. The **TCLF (Textiles, Clothing, Leather, Footwear) Skills Alliance** and similar initiatives should integrate modules on robotics operation, AI, and data analytics for textiles. These programs should prepare workers to transition to higher-tech roles (robot technicians, digital fabric designers, etc.). EU Social Fund resources and national schemes should be aligned to anticipate the shift in job profiles.
- **Research to Market Pathways:** The EU should continue funding high-risk, high-reward research (e.g. in **soft robotics, tactile sensing, simulation of deformable materials**) while simultaneously improving mechanisms for licensing the generated IP and commercializing successful innovations. The EU and member states should support pilot adoption by using automated local production for public sector needs (such as military uniforms or hospital linens), providing an initial market and learning opportunity.
- **International Collaboration and Standards:** The challenge of RTM is global. Europe should initiate and lead joint forums or working groups via IEEE or ISO to develop **standards for robotic handling of soft materials**, ensuring interoperability, fabric handling metrics, safety norms for human-robot collaboration in textile tasks, and data formats for material properties. Europe's active role in such standard-setting would support its companies in accessing global markets with their solutions.

In conclusion, Europe has built a **solid foundation** in robotic textile manipulation through a decade of focused R&D and is backed by a strong socio-economic impetus to automate. European projects have delivered promising building blocks, from AI vision systems that can detect and grasp limp fabrics, to novel grippers inspired by biomimetics and vacuum techniques, to integrated cells that perform delicate tasks like lingerie fabric stacking and inspection. Policy support is evident, and pioneering industry trials show that automated production can be viable in Europe, delivering quality and consistency with reduced labor input. However, the alignment is not yet complete: the pace of translating innovation to industry must quicken, and remaining misalignments, whether in skills, economics or technology, should be addressed through coordinated action. With sustained effort, Europe can leverage RTM not only to **revitalize its textile manufacturing** in a sustainable, competitive way, but also to **secure a leadership role** in the next generation of intelligent robotics that handles the hard jobs of soft materials.

1 Introduction

The handling of textiles, from individual yarns and fabrics to finished garments, has long been one of the most labor-intensive aspects of manufacturing. Unlike rigid parts, textiles are deformable, drapeable, and can continuously change shape when manipulated, posing unique challenges to automation. As a result, the textile and apparel industry has remained heavily reliant on manual labor well into the 21st century, in stark contrast to sectors like automotive or electronics that have seen extensive robotic automation. This report examines Europe's pursuit of *robot textile manipulation (RTM)* capabilities in the last decade (with emphasis on 2015–2025), assessing how well Europe's strengths in research and technology align with its industrial needs and socio-economic drivers in this domain. We explicitly adopt a **triple-view across the textile life-cycle**, considering RTM in (a) production and intra-factory handling, (b) distribution and reverse logistics (including warehousing, e-commerce returns, and industrial laundry), and (c) end-of-life processing (sorting and recycling of textiles). Below, we introduce each of these phases and their relevance to RTM.

Robot Textile Manipulation (RTM) refers to the use of robotic systems to handle, process, and assemble textile materials (fibers, fabrics, garments) autonomously or semi-autonomously. Example tasks include automated fabric cutting and handling, sewing or joining of garment pieces by robots, robotic folding and packaging of clothes, and even advanced applications like assisted dressing or textile recycling by robotic means. Technologically, RTM is a subset of the broader field of deformable object manipulation in robotics, which deals with objects that are not rigid bodies [72]. Mastering RTM requires innovations in several areas: *perception* (so robots can recognize and track limp materials), *gripping and manipulation mechanisms* that can adapt to flexible materials, *modeling and simulation* of textile physics, and *planning/control algorithms* that can handle the high dimensionality and uncertainty inherent to cloth states. Throughout this report, we revisit these scientific challenges (detailed in Section 3) and how they are being addressed.

From a policy and economic standpoint, interest in automating textile manufacturing is driven by multiple factors. Europe historically was a global center of textile and garment production, but over the past decades, much of this production has moved to Asia and other low-cost regions. Today, Europe faces strategic questions: can advanced automation enable a degree of *reshoring* of textile manufacturing? Could robotics address the cost and labor challenges and thereby **strengthen Europe's textile supply chain resilience**?. These questions have taken on renewed urgency with recent events. The COVID-19 pandemic revealed vulnerabilities in long, overseas supply chains (e.g. difficulties in sourcing face masks and medical textiles early in the pandemic), reinforcing the appeal of having local automated production capacity for critical textile products [58] [75]. Moreover, rising wages in Asia and the drive for sustainability (reducing the carbon footprint of shipping goods globally, improving labor conditions) make a case for shorter, more automated supply chains [13]. At the same time, new EU policies, notably the **EU Strategy for Sustainable and Circular Textiles (2022)** [40], are pushing for circularity, which includes better textile recycling and waste reduction. Automation is increasingly seen as an enabler for these goals, by making local production viable and by handling the growing volumes of textile waste and returns that must be processed.

Within the European Union's research and innovation agendas, RTM has gained prominence under initiatives aimed at the **digital transformation of industry** and **advanced manufacturing**. The Horizon 2020 framework (2014–2020) and the current Horizon Europe program

(2021–2027) both identified automation of *flexible materials* as a critical research challenge. In 2018–2019, the EU launched a specific call (DT-FOF-12-2019) targeting "handling systems for flexible materials" [22], which explicitly highlighted textiles and soft objects as a domain where automation was lagging behind and novel solutions were needed. The funding of multiple projects from that call signaled an official recognition that RTM capabilities were necessary for Europe's industrial future. This dovetails with European industry roadmaps; for instance, the European Factories of the Future Association (EFFRA) roadmap pointed to "flexible material handling" as a priority to enable agile and reconfigurable production lines [45].

This white book is structured to first provide an overview of the **technological context** of RTM (Section 2), the current **scientific challenges** (Section 3), and then delve into Europe's capabilities and R&D trends (Section 4). Section 5 maps the **socio-economic drivers** that underscore the importance of RTM in Europe, from labor market issues to sustainability goals. In Section 6, we identify **key actors** across research, industry, and policy, illustrating their roles with case studies and expert commentary. Section 7 offers a **comparative analysis** of how Europe's efforts stack up against developments in the US and Asia, providing a global context. We then critically evaluate (Section 8) whether Europe's current trajectory aligns with what is needed for RTM to become economically and technically viable, including discussion of challenges and skeptical viewpoints. Finally, Section 9 presents **recommendations** for policy and investment measures to enhance Europe's strategic position in robot textile manipulation, followed by a short conclusion (Section 10).

Throughout the report, a mixed-methods approach is used: we synthesize insights from academic literature (including a 2024 comprehensive review of robotic cloth manipulation), analyze EU project results and policy documents, and incorporate statistical data and commentary from industry experts. All sources are cited in IEEE style, with persistent identifiers, to allow verification and further reading. The aim is to provide a thorough and forward-looking assessment that can inform EU policymakers, research strategists, and industry stakeholders on aligning Europe's capabilities with the needs and opportunities in automating textile production, handling, and recycling.

1.1 RTM In Production and Intra-Factory Handling

The **production phase** covers the manufacturing of textile materials and products – including fiber and fabric processing, garment assembly (sewing), and intra-factory handling of textile pieces. This is the phase where RTM can potentially enable Europe to *"bring back"* or **reshore** certain manufacturing activities by substituting or augmenting manual sewing and handling labor with robotics. Key tasks in production include fabric cutting, piece picking and placement, sewing operations, joining and seaming, as well as post-assembly tasks like automated folding and packaging of finished garments. Traditionally, many of these tasks (especially sewing assembly) have proven extremely difficult to automate due to the flexibility of fabrics. Even today, a high-end garment might pass through dozens of manual operations (stitching, hemming, attaching components) because robots cannot yet replicate the dexterity of human fingers in manipulating limp cloth. However, recent advances are closing this gap. For instance, robots have demonstrated basic competence in tasks like **automated t-shirt sewing**, the American startup SoftWear Automation's "Sewbot" system can sew simple garments using machine vision to guide fabric under a fixed sewing head, though such systems are currently limited to specific products and require significant capital investment [4] [94].

Europe's interest in production-stage RTM is driven by several **socio-economic drivers** detailed later (Section 5): rising labor costs in Europe (which make local production of labor-intensive textiles uncompetitive), labor shortages (few young workers entering sewing trades), and the desire for supply chain resilience and agility (e.g., being able to produce PPE or fashion goods quickly within Europe). RTM in production promises not only cost reduction but also consistent quality and the possibility of manufacturing innovative products (e.g., smart textiles) that may require precision handling beyond human capability. Yet, the **scientific challenges** here are significant: a robot in a factory must reliably handle a variety of fabrics (from stiff denim to delicate lace) at speeds approaching human throughput, and adapt to variability in material behavior. Section 3 discusses challenges like **highly deformable fabric manipulation** (e.g., preventing limp silk from slipping or distorting during handling) and **energy-efficient soft grippers** (for gentle yet fast grabs), all directly relevant to production automation. Europe's R&D projects, such as new gripper designs (electroadhesive, vacuum, etc., see Sec. 2.3) specifically target these production-phase issues.

1.2 RTM In Distribution, Logistics, and Reverse Logistics (Use-Phase)

The **use-phase** of textiles involves all the logistics and handling that occur after manufacturing, including distribution of finished goods (warehousing, sorting, and shipping garments to stores or customers) and reverse logistics processes like handling customer returns and industrial laundry. Automation in this phase is increasingly important due to the growth of e-commerce (leading to higher return rates) and chronic labor shortages in sectors like warehouse logistics and commercial laundry. While not traditionally highlighted in earlier RTM discussions, these areas present **immediate opportunities for RTM deployment** because the tasks, though still dealing with deformable items, often involve more structured scenarios than sewing. For example, an industrial laundry processes thousands of identical towels or sheets daily – a task where a robot can be trained to repeatedly pick, spread, and feed such flat fabrics into folding machines. Indeed, European startups have seized on this: Munich-based **Sewts** developed the VELUM system for laundry automation, which uses dual robotic arms and AI to feed terry towels into a folder. As of 2023, VELUM installations (e.g., at Greif Textile Mietsysteme in Germany) handle 500–600 towels per hour – matching human performance – and can pay for themselves in under 2 years [56]. This exemplifies RTM applied to *inverse logistics*: a post-use handling process (laundering) where robotics can alleviate labor shortages and improve throughput.

Similarly, **warehouse and distribution centers** for apparel increasingly look to robots for picking and sorting. While rigid-item warehouses (like for electronics or groceries) have widely adopted automation (robotic shelf pickers, conveyor systems), handling apparel still presents challenges: clothing items can drape or flop, making them harder for a vacuum gripper to pick. Nonetheless, progress is evident. Companies like **Berkshire Grey** [9] and **Kindred (Ocado)** [53] have demonstrated robotic picking of apparel in warehouse settings using AI vision to identify graspable parts of a garment. Reverse logistics is particularly critical in fashion e-commerce: Europe sees an average online clothing return rate of 2̃0–30% (one in five garments sold online is returned) [44], leading to **millions of items that must be inspected, sorted, restocked or recycled** annually -which is still much better than simply destroying them, as is often the case. Automation can reduce the cost and time of processing these returns. Sewts, for instance, is already extending its technology to handle textile returns in fulfillment centers, aiming to automatically sort and grade returned apparel, a process that today is labor-intensive and often offshored (some European returns are baled and shipped to low-wage countries for sorting) [56]. By automating domestically, Europe could avoid shipping returns overseas (saving cost and emissions) and recover usable products faster.

The logistics and reverse logistics phase offers a *relatively structured* arena for RTM: tasks like **bin picking of garments, folding/sorting, and feeding items to machines** can often be broken down into repetitive actions where robots excel, provided perception is robust. The scientific challenges here revolve around **perception under occlusion** (e.g., identifying a single garment in a jumbled returns bin) and **planning grasps for varied items** (different clothing types, sizes, or damp laundry). Section 3 discusses how scalable grasp planning algorithms and multi-modal perception (combining vision with touch) are being developed to tackle these issues. Economically, automating these mid-stream processes can directly improve margins for European retailers and service providers by cutting labor costs and enabling faster turnaround (e.g., a returned item could be robotically sorted and back on sale in a day, rather than weeks). The socio-economic drivers detailed later (Section 5) show that companies are urgently seeking such solutions – for instance, a UK survey found warehouse operators facing $>30\%$ annual labor shortfall in sorting jobs, indicating strong demand for automation.

1.3 RTM in End-of-Life: Textile Sorting and Recycling

The **end-of-life phase** for textiles involves collecting used textiles, sorting them by material or condition, and processing them for recycling or disposal. This aspect has gained prominence due to Europe's sustainability and circular economy goals. EU Member States must implement **separate textile waste collection by 2025**, reflecting a policy push to avoid landfilling and incineration of the $\tilde{7}$ million tonnes of textile waste generated annually in the EU [43]. However, one major bottleneck in textile recycling is the *sorting* of heterogeneous textile waste. Today, much sorting is manual or semi-automatic, and it's costly and slow to grade textiles by fiber type (cotton vs polyester vs blends) or by quality (reusable vs recyclable vs waste). Robotics and AI are poised to revolutionize this stage: automated systems can potentially identify material composition via sensors and separate textiles at high throughput, something manual sorting cannot scale to. Europe has been a pioneer here: **Siptex** in Sweden is the world's first large-scale automated textile sorting plant (opened 2021). It uses optical sensors (near-infrared spectroscopy) and automated conveyor diverters to sort textiles into categories by fiber content and color, at a capacity of $\tilde{4}.5$ tonnes per hour [74]. While Siptex's current system is more of an advanced machine line than a "robot with arms," it lays the groundwork for integrated robotic sorting (e.g., robotic arms could pick out specific garments from a mixed pile for higher precision sorting).

Another frontier is **robotic disassembly or recycling processes** – for instance, using robots to carefully unstitch garments or remove buttons/zippers before recycling the fabric. Though at early stages, research is exploring such targeted automation to improve recycling quality (removing non-textile components or sorting by color to avoid dye contamination in recycling). The Horizon Europe project **FlexCycle (2025–2029)** [104], for example, will portray a use case on robot textile disassembly. Similarly, some startups use modified robotic arms to pull apart shoes (a complex composite of leather, textile, rubber) for material separation [37].

From a **life-cycle perspective**, end-of-life RTM completes the circle: robots that help turn old clothes into sorted feedstock for new textiles make the entire supply chain more sustainable.

The socio-economic impetus is clear – the EU wastes billions of euros in thrown-away textiles each year and faces environmental costs from incineration and exporting waste [46]. Automation can significantly reduce processing costs for textile recycling, enabling more recycling plants within Europe. It also addresses the labor issue: sorting dirty, mixed textile waste is a job few people aspire to, and some regions rely on low-wage labor abroad to do it (as noted, used clothing from the EU often ends up in African or Asian markets where local labor sorts it for reuse or disposal). Robotic sorting could allow Europe to internalize this process, creating jobs in high-tech recycling rather than burdening developing countries with our cast-offs.

That said, there are technical challenges: textile waste comes in unpredictable forms (torn, soiled, knotted in bags) and robots must handle **high variability and contamination**. Perception systems need to identify materials even if colors are faded or items are crumpled together. Soft grippers may be needed to handle fragile old textiles without shredding them further. We discuss in Section 3 how challenges like **occluded perception** and **robust manipulation** are being tackled with advanced sensing (e.g., hyperspectral cameras to identify fiber content) and learning algorithms. Encouragingly, case studies show feasibility: the German company **SOEX** [92] developed an automated sorting system for recycling purposes, resulting from the RESYNTEX [21] EU project, among other European examples [97].

2 Technological Context of Robot Textile Manipulation

Robotic manipulation of textiles is **technologically complex** because textiles exhibit properties fundamentally different from the rigid parts robots traditionally handle. In a rigid object, a robot can predict how the object will move when forces are applied; in a textile, however, forces cause continuous deformation as the material bends, folds, or stretches, and its shape at any moment depends on its entire history of handling. A limp piece of cloth has effectively infinitely many possible configurations, making its "state" hard to measure or plan for. Key technical challenges in RTM include **perception and state estimation**, **physical modelling and simulation of cloth**, **specialized gripping/end-effectors**, and **manipulation techniques and planning** tailored to deformable materials. This section provides an overview of these challenges and the progress to date. Section 3 complements this by focusing on open scientific challenges and research directions.

2.1 Perception and State Estimation

A robot must perceive a flexible object that does not have a fixed shape. Vision systems struggle with textiles because of self-occlusion (parts of a garment can cover other parts), varying appearance (wrinkles, folds change visual features), and the need to infer 3D shape from 2D images. Depth sensors often fail on thin fabrics. Recent approaches use *RGB-D cameras*, sometimes combined with *machine learning*, to recognize garment keypoints or to classify the state of a clothing item (e.g. spread out vs. bunched up) [72]. For instance, one system can look at a crumpled towel and identify where a corner is likely located for the robot to pick. Tactile sensing can also help, for example, by feeling edges or thickness. A notable advance is the development of simulators for cloth, which allow synthetic data generation and training of perception algorithms; physically accurate cloth models (incorporating material properties like stiffness and elasticity) are improving [29, 72]. Yet, perception remains a bottleneck, as it is non-trivial for a robot to, say, pick up a randomly crumpled piece of clothing and identify its corners or orientation reliably. Many systems still rely on heuristics (like "pick the lowest hanging point of a garment" which often is a corner). Occlusion is a particularly thorny issue: when a garment is folded over itself, even humans struggle to instantly know its state – robots often must perform *interactive perception* (i.e., manipulate the item a bit to reveal new views, such as shaking or spreading the cloth). In summary, while great progress has been made in perception (deep learning has enabled detection of grasp points with some success [72]), achieving *human-like understanding* of a garment's shape and condition through vision/touch is still an open challenge (see Sec. 3.2 for research efforts on occlusion and multi-modal sensing).

2.2 Modeling and Simulation

Predicting textile behavior under robot actions is a complex physics problem. Current popular simulators, like Isaac Sim, SOFA, or MuJoCo use mass-spring models or finite element models, but achieving real-time performance and sufficient accuracy is hard. The EU-funded CLOTHILDE project worked on physically-accurate modeling of textiles for simulation of cloth manipulation [29].

Advanced models must capture phenomena like friction between layers, fabric stretch under tension, and even air resistance (important for lightweight fabrics). Having a good model is vital for planning actions: if a robot can simulate "if I pull here, the fabric will fold like so," it can plan better strategies. However, given the difficulty, many current solutions bypass explicit physics modeling and instead use learning-based approaches, letting the robot learn manipulation policies from trial and error or from demonstrations, effectively treating the cloth as a "black box" dynamic system [10, 20, 73]. For example, reinforcement learning in simulation has trained policies for folding a cloth without the robot explicitly calculating physics; the policy just learns that certain motions lead to desired outcomes over many trial runs. This can work well for specific tasks, but may not generalize widely. One emerging compromise is using differentiable simulations (simulators that a learning algorithm can tune to match real-world behavior) In Sec. 3.4 we highlight that achieving fast, accurate simulations remains a grand challenge. Solving this would unlock better planning: a robot could "imagine" the result of a complex sequence of moves on a garment and choose an optimal sequence rather than blindly executing a fixed routine.

2.3 Gripping and End-Effectors

Traditional robot grippers (two-finger pinch grippers) have limited efficacy on limp materials. Textiles can slip out or require large surface contact to be held without damage. A variety of specialized end-effectors have been devised in RTM research:

- **Pinch grippers:** Thin, compliant finger grippers can pinch a piece of fabric at a point (such as grabbing a shirt by the collar or a sheet by the hem). Their slim, compliant nature allows them to pinch only the intended layer and not multiple layers.
- **Vacuum grippers or suction cups:** Widely used in textile manufacturing for tasks like moving fabric sheets, suction grippers create negative pressure to "stick" to a fabric region. These can quickly pick up even very floppy fabrics on any accessible surface. However, suction may struggle if the fabric is porous or if precise positioning is needed (it grabs a general area).
- **Electro-adhesive grippers:** Developed in the MERGING project, use electrostatic charges to make a surface "sticky" to cloth [30]. This method can hold delicate fabrics without high pressure, reducing damage and adapting to different shapes.
- **Universal jamming grippers**: These are membrane bags filled with granular material (like coffee grounds); when pressed onto an object and vacuumed, they mold around it and then harden, "jamming" into a solid grip. Some labs tried these for deformables – e.g. pressing onto a pile of fabric so the granules conform and then lifting the pile. They can grip irregular shapes but are slow to cycle and not textile-specific.
- **Multi-fingered robot hands** Dexterous robot hands (with three or five fingers) have also been tested. In principle, they could grasp fabric similarly to a human hand (e.g., pinch with thumb and index, or use multiple fingers to drape a cloth over them). However, controlling many fingers to coordinate on a deformable object is extremely complex, and such hands are usually more fragile/expensive. So, they remain more in the research realm for now.
- **Novel designs**: Researchers have explored alternative mechanisms tailored to the challenges of grasping thin, deformable, or fluttering textiles. These include **roller-based**

grippers [48], which can pull fabric in a controlled manner without piercing or pinching it, and **airflow-assisted or flow-based grippers** that use directed jets to manipulate fabric position and facilitate grasping, sometimes leveraging the **Coandă effect** [69]. Other innovations include **shape-memory alloy (SMA)-based grippers** [91, 71] and **magneto-rheological or electroactive polymers** [107, 18], which adapt their shape or stiffness dynamically to the object being manipulated. These approaches aim to increase adaptability, reduce mechanical complexity, and minimize damage when handling delicate textiles. A challenge though is durability and speed: some soft actuators (like SMAs) are slow or use significant power for large motions, so research continues into balancing **grip strength, speed, and energy efficiency** (Section 3.5 will revisit how energy-efficient soft grippers remain a research frontier).

No single gripper works for all textile tasks; thus, many systems employ a combination, or tool-changing. A trend is making grippers *intelligent*, i.e., integrating force/torque or tactile sensors so the gripper can detect when it has a fabric securely or if it has multiple layers, etc. For example, KUKA and Robotextile's solution uses sensors to ensure only one layer is picked up from a stack [66].

2.4 Manipulation Techniques

Beyond picking something up, RTM includes actions like **spreading** a cloth on a table, **folding** or **wrapping** fabrics, **inserting** pieces (like threading a sleeve), or **sewing** along a seam. Robots can execute these via a variety of techniques:

- **Bimanual manipulation:** Two arms working together to stretch or fold a textile. Many lab demonstrations (e.g. folding a towel) use dual-arm robots holding two corners. Coordination and mirror-symmetric control are needed. Research has provided algorithms specifically for two-armed cloth manipulation, such as ensuring the arms move such that the fabric stays tense [51].

- **Using environmental constraints:** Rather than doing everything mid-air, robots can use support surfaces or tools to assist. For instance, humans often lay a shirt on a table to fold it. Similarly, a robot can use the table as a "third hand" to lay out fabric. Hooks, poles, or specially shaped surfaces can help too. The Horizon Europe *SoftEnable* project explicitly explores *"soft fixture-based manipulation primitives"* – using semi-rigid supports or jigs to temporarily constrain a deformable item and make it easier to handle [32].

- **Learning from Demonstration (LfD):** Instead of programming every motion, LfD (also called imitation learning) lets a human physically demonstrate the task for the robot to replicate. For cloth, a human might guide a robot's arms through the motions of putting on a hospital gown onto a patient, and the robot records this trajectory. Projects like a CLOTH manIpulation Learning from DEmonstration (CLOTHILDE [29]) have applied LfD to tasks like bed making. This is useful for complex multi-step tasks where analytic programming would be very hard (like dressing a person in a jacket). In conjunction, reinforcement learning in simulation has been used: e.g., a robot can virtually practice smoothing a wrinkled fabric with a reward for how flat it becomes, eventually learning a strategy.

- **Task and Motion Planning:** High-level planning for textiles often involves a sequence of steps that must be planned with both discrete decisions (what step next) and continuous motions. For example, to fold a shirt, the "task plan" might be: grasp the collar and bottom, stretch, put on the table, fold sleeves, then fold in half. Each of those steps has continuous motions. This is referred to as TAMP (task and motion planning) [50]. The robot might need to plan a sequence of moves that gradually achieve a desired configuration (like a neatly folded towel), accounting for how each move changes the cloth shape [67]. The complexity means many assumptions or simplifications are made (like planning only corners' positions instead of full cloth shape). Nevertheless, progress in this area could allow robots to break down complex jobs into manageable steps systematically, which is crucial for general-purpose textile robots that might one day perform arbitrary new tasks.

2.5 Integration with Sewing Machines

One of the ultimate goals is robotic sewing – having a robot perform the complete assembly of garments which currently involves skilled human machinists. This is essentially an *industrial robotics meets sewing machinery* problem. Some approaches keep the sewing machine stationary and have a robot handle the fabric under the needle (e.g. guiding the fabric through a sewing machine, but requires extreme precision to follow seam lines). Other experimental approaches include using robots to position pieces and even using alternative joining techniques (like ultrasonic welding for textiles). A notable concept (by the American startup Sewbo and related ARM projects [4, 89]) is to temporarily **stiffen the fabric** (e.g. with a dissolvable polymer) to make it behave like a flexible plastic sheet that a robot can handle more easily for sewing, then wash the garment to remove the stiffener. Europe's research has also looked into such **material aides** or smart materials that simplify handling during automation [87, 45]. Fully robotic sewing is not yet mainstream, but partial automation, e.g. automated placement of patches or pockets for sewing, or automated feeding of pieces to human workers in a co-working setup, is being developed.

In summary, the technological building blocks for RTM are advancing rapidly. The confluence of improved sensors, more powerful computing (to run physics simulations or AI models), and novel robotic mechanisms has led to a flurry of progress in the last ten years. Europe's role in this progress is significant, as seen by its many projects tackling different facets of the problem (from fundamentals to prototype systems). However, as subsequent sections will explore, significant **R&D efforts have yet to culminate in turnkey solutions** that can be widely adopted in industry. The technology is evolving, but still maturing; the gap between what a controlled lab setup can do with a piece of fabric and what a factory floor needs in terms of robustness and speed is non-trivial. The next sections delve into how Europe has been addressing these challenges through its capabilities and initiatives, and how these efforts align with industry needs and global competition.

3 Scientific Challenges in RTM

While Section 2 surveyed the technological context and partial solutions, this section focuses on the core *scientific and engineering challenges* that remain open in robot textile manipulation. These challenges define the frontier of research and are the subject of intense study in the robotics community. We highlight five interrelated challenges: **(i) manipulation of highly deformable fabrics, (ii) perception under occlusion and uncertainty, (iii) scalable grasp planning and generalization, (iv) real-time simulation and dynamics prediction, and (v) energy-efficient and versatile soft grippers**. Addressing these issues is crucial for advancing RTM to the point of economically viable deployment across the textile life-cycle.

3.1 Handling Highly Deformable and Variable Fabrics

Textiles come in a vast range of materials with different behaviors: compare a flimsy silk chiffon, a stretchy knit T-shirt, a heavy wool sweater, and a springy Lycra athletic wear. A major scientific challenge is enabling robots to handle highly deformable fabrics and **generalize across different material properties**. Most robotic solutions to date work on a limited set of fabrics (often relatively stiff or medium-weight cloths). When confronted with something very deformable (extremely thin or elastic), those methods can fail. For instance, a vision algorithm trained on cotton towels might not recognize the crumpled shape of a silk scarf; a gripper designed for a denim piece might apply too much force and slip off a Lycra sheet. The 2024 comprehensive review by Longhini et al. notes that progress in the field has often been tailored to one specific textile or subcategory, and methods struggle to generalize to a broader range of real-world textiles [72]. Key open problems include: how to identify the relevant physical properties (stiffness, thickness, friction, weight) of a textile quickly, so the robot can adjust its strategy? And how to do so when those properties can change (a wet cloth vs dry cloth, or an aged garment whose fabric has weakened)?

Robots currently lack the adaptability that humans have, we intuitively handle a silk blouse more gingerly than a canvas tarp. Some research is exploring ways to measure or classify fabric properties on the fly. For example, having a robot perform a quick exploratory action like a droop test (lift and see how much it drapes) or a stretch test (pull and measure resistance) to gauge stiffness [49]. The concept of dynamic fabric property estimation is emerging: a robot might use multi-modal sensory feedback (vision to see the sag, force sensors to feel resistance) to estimate parameters like bending rigidity or damping [19]. However, as identified in the literature [72], the influence of each property on manipulation is underexplored, and it's unclear which subset of features (e.g., weight vs thickness vs friction) is most pertinent for different tasks. Developing a minimal but sufficient "fabric descriptor" that robots can use for planning is an open challenge.

Moreover, fabrics change under conditions: **humidity, wetness, dirt, temperature** can all alter behavior (a wet cotton cloth is heavier and more adhesive; a dirty cloth might have mud making it stiffer in spots). This means robots might need continuous sensing and adaptation even for the same textile. The introduction of *semantic descriptors* ("smooth", "slippery", "stretchy") and using machine learning (like large language models) to relate those to physical parameters is a novel idea being floated, for instance, if a robot's AI knows "silk = slippery", it could anticipate higher chance of slip and adjust grip strategy [109].

A particularly deformable scenario is handling very lightweight or highly elastic fabrics. These can flutter with air currents and stretch significantly, adding complexity. To date, few robots can robustly handle, say, a latex sheet (extremely elastic) or a piece of tulle (extremely light and flimsy). These represent edge cases that are common in fashion and technical textiles. The grand challenge is to develop manipulation strategies that cover the whole spectrum of deformability. One promising direction is **adaptive control**, controllers that can adjust on the fly to the measured behavior of the material. For example, adaptive force control might pull just until a certain extension is detected and then stop to avoid overstretching a fabric.

3.2 Perception Under Occlusion and Uncertainty

Perception remains a fundamental challenge in RTM. In real-world scenarios, textiles are often in unstructured piles (occluding themselves), in varying lighting or against complex backgrounds (making vision harder). Occlusion means a robot's sensors only see part of the textile; the rest is hidden underneath folds or other items. Humans deal with this by leveraging experience ("if I see a seam here, likely it's the shirt's side seam, meaning a sleeve is occluded over there") – robots need to develop similar inference abilities. Many current systems mitigate occlusion by simplistic means: e.g., spread the cloth out first so it's mostly visible, or pick it up and let it unfold partially. But these add steps and time.

A scientific frontier is *interactive perception*: perception and manipulation done together in a feedback loop. Instead of a static "observe then act" strategy, the robot might perform probe actions purely to improve perception, like lifting one corner to shake out a cloth (revealing it fully) or using a second arm to hold a part up while inspecting another part. This is challenging to plan (the robot must guess what action will yield the best information). Early research hints that multimodal sensing is key [72]: integrating visual data with tactile and even auditory feedback (the sound of rustling can indicate if a piece is dragging) to form a more complete picture. For instance, when a robot grasps a bunched garment, tactile sensors can tell if it has one layer or multiple, and vision can maybe identify which part (hem, sleeve...) is in hand. Combining these can reduce uncertainty about the state.

Another issue is state representation under uncertainty. Unlike a rigid object, where a pose (position/orientation) fully describes it, a garment has infinitely many degrees of freedom; in practice, robots define the state in simplified terms (e.g., "folded once" or "inside-out vs right-side-out"). Under occlusion, a robot might not know the exact state (like whether a shirt is inside-out). Systems need to either actively resolve that (flip it to check) or handle contingencies (try an operation and see if the result is as expected, if not, adjust) [108]. *Probabilistic state estimation* approaches have been tried: maintaining a belief over possible cloth states and updating it with sensor info, as one would do in SLAM for robot localization. This is computationally difficult but an area of ongoing research.

Deep learning has significantly advanced cloth perception, and convolutional neural networks can classify garment type from images and can sometimes even predict keypoints (like collar or cuffs) with training. But these networks struggle if the garment is in an unusual configuration not seen in training. Occlusion exacerbates this because parts of the garment the network expects to see are hidden. The push now is to go beyond large labeled datasets to more general 3D understanding [6]. One approach is to train networks on simulation data where the full state is known, and have them output, say, a partial shape estimate or a set of likely shape candidates for the real observation. Additionally, transformer-based vision models and neural radiance fields (NeRFs) are being investigated to reconstruct 3D surfaces of cloth from a few views [63].

3.3 Scalable Grasp Planning and Manipulation Generalization

"Grasp planning" in RTM refers broadly to deciding *where* and *how* a robot should grasp or contact a textile to achieve a goal. This is far more complex than for rigid objects. With a rigid object, algorithms can compute stable grasp points based on shape. With cloth, the shape itself depends on how it's grasped. Moreover, a single garment presents many possible grasp points and the "best" one depends on the task (to unfold a shirt, grasping a corner might be best; to put it on a hanger, grasping the collar might be better).

A core scientific challenge is to develop planning algorithms that scale with this complexity and yield robust strategies. Early approaches often resorted to heuristics (e.g., "always pick the topmost point of the pile" which tends to be a corner or edge). While simple and sometimes effective, these are not guaranteed or optimal. More recent work tries to incorporate learning-based planners: for example, using deep reinforcement learning to learn a policy that, at each step, picks a grasp and motion that incrementally improves the cloth's state (like flattening it out). Such policies can be good but are often narrow in scope (trained for a specific garment or fold type).

The term "scalable" implies methods that can handle larger and more complex tasks without exponential blow-up in planning time. One can imagine that a robot tasked with assembling a multi-piece garment would need to plan a sequence of dozens of grasps and moves. Exhaustively searching that space is intractable. Instead, researchers look at hierarchical planning: breaking tasks into sub-tasks (e.g., first lay out piece A, then align piece B, then join) [110]. Deciding these sequences automatically is an open research area. Classical AI planning might be used if one can define states like "piece A positioned" etc., but defining those in cloth terms is hard.

The challenge of generalization ties in that we want a single planner that can handle many garment types and tasks. Right now, many solutions are bespoke (one for folding towels, another for unfolding shirts, etc.). A unified framework, perhaps one that takes a description of the garment and desired end-state and then computes a plan, would be ideal. Some progress is being made: a 2022 study introduced a system that could take in a high-level instruction like "fold the garment in thirds" and plan motions, by leveraging a learned library of skill primitives [106]. However, truly flexible general planners remain beyond current capabilities.

In terms of evaluation, there has been a lack of standard benchmarks, though the community has started creating them (e.g., a common set of garment manipulation tasks for all algorithms to attempt). This will help measure progress in scalable planning. But a grand challenge identified is developing an *adaptive multi-task, multi-modal agent* that can handle long-horizon tasks and use multiple sensory inputs [72], essentially the kind of generalist cloth-handling robot that can plan through complex sequences reliably. Achieving this will likely require integrating many techniques: analytical models, learning, simulation, and perhaps new representations (like graph-based representations of cloth state that simplify planning).

3.4 Real-Time Physics Simulation and Prediction

As highlighted in Sec. 2.2, a major technical barrier is the lack of fast and accurate simulators for cloth. This is not just an engineering problem but a scientific one: cloth dynamics are governed by nonlinear partial differential equations, which are computationally expensive to solve. Moreover, real fabrics have properties like plastic deformation (permanent creasing) or anisotropy (different stiffness in different directions of weave) that are hard to model fully. The result is that planning and control algorithms often operate without a good predictive model, essentially "flying blind" compared to rigid-body robotics, where physics engines are extremely reliable and fast.

The challenge here is two-fold: speed and fidelity. For real-time control, a simulator needs to predict cloth response in milliseconds. Current high-fidelity simulators might take seconds to simulate one second of complex cloth movement, which is too slow for feedback control. On the other hand, simplified models (like treating a cloth as a linked chain of points) run fast but might deviate significantly from reality, leading to errors (e.g., predicting a cloth will fold nicely when in reality it might crumple). Bridging this gap may require novel approaches: one idea is using machine learning to create surrogate models of cloth physics. For instance, training a neural network to imitate the cloth's behavior (learning from data generated by a slower simulator or real experiments) and then using that neural network inside the control loop. There are examples of this in 2023–2024 literature where neural nets predict the outcome of simple cloth manipulations much faster than physics simulation would, albeit in limited scenarios [84, 16].

Another promising direction is parallel computing. Modern GPUs can handle certain physics computations in parallel, and projects like NVIDIA's Flex and Warp are exploring accelerating deformable object simulation. Yet, the issue is not just raw computation – there's also uncertainty in material parameters. Two seemingly identical fabrics can behave slightly differently; so a simulation that is even moderately off can lead to a plan that fails on the real fabric. Thus, simulation and reality mismatch is a key concern (the sim2real gap). To address this, researchers are exploring online model updating, using sensor feedback to update the simulation parameters on the fly, making predictions more accurate [10, 11].

Ultimately, achieving real-time predictive simulation might require hybrid approaches: using analytical models where they work (e.g., small linear deformations) and switching to learned corrections for complex behaviors. It's a grand challenge to reach the point where a robot can "think ahead" about cloth as easily as it does for rigid parts. The grand challenges list in Longhini's survey [72] includes developing novel datasets and benchmarks to evaluate generalization, highlighting that without common yardsticks, simulation progress is hard to gauge. The field recognizes this and is moving toward more rigorous comparisons of simulation and reality.

3.5 Energy-Efficient and Soft Gripping Mechanisms

Effective manipulation of textiles requires grippers that are delicate (to not damage material), adaptive (to conform to varied shapes), yet strong and fast. Soft robotic grippers (made of compliant materials or using soft actuators) have shown great promise, but they come with trade-offs, notably in actuation speed and energy consumption. For example, a pneumatic soft gripper can gently envelop a fabric, but it needs an air compressor, which is energy-intensive and bulky. Electroadhesive grippers use high voltage but low current, making them energy-efficient to hold fabric (they need power only to charge, then very little to maintain adhesion). However, they might struggle with very heavy fabrics or require very clean fabric surfaces to adhere well (dust or lint can reduce effectiveness).

The scientific challenge here is designing gripping mechanisms that balance competing demands: they should be low-power, lightweight, and capable of rapid operation, all while providing a secure grip on flexible material. Traditional industrial robots did not worry about energy much (they are plugged into mains and mostly deal with rigid parts, so short bursts of high power are fine). But imagine a mobile robot sorting clothes – it might run on a battery, so gripper energy efficiency becomes important for operating hours. Also, some advanced grippers, like jamming grippers, need vacuum pumps running continuously to maintain grip, which is inefficient.

One research avenue is bistable or tristable grippers – grippers with mechanical or material states that require no power to maintain. A recent study on a tristable SMA-based gripper [59] developed a design that has three stable states; the gripper can latch onto an object, and then power can be cut while it remains latched (due to mechanical locks). Such designs could significantly reduce energy usage during holding phases (which in many tasks is a large portion of the cycle). Electro-permanent magnets are another example (not yet used widely in textiles, but conceptually): magnetize to grip a piece with embedded magnetic particles, then no power is needed to hold until demagnetized.

Electroactive polymer (EAP) actuators are highlighted for their energy efficiency. They can directly strain under electric fields with fine control and relatively low energy loss, though many require high voltages. An advantage is that they can be made into thin, flexible surfaces – ideal for a "skin-like" gripper that conforms to a fabric. EAPs have high energy efficiency, low driving voltage, and fine control, making them attractive, but sensitivity to the environment and the need for specialized power electronics is a challenge [15].

Another angle is design simplicity: the more complex a gripper (with many motors or valves), the more points of energy consumption and potential failure. Researchers are exploring minimalist designs, like using a single motor to achieve a multi-finger wrap via clever tendon routing, etc. Origami-inspired grippers have been developed that can switch shape with one actuator to wrap around objects [64].

For textile-specific grippers, maintaining hold with minimal force is key to efficiency. Think of holding a piece of paper by pinching lightly near the top edge – minimal force if balanced. For fabric, if the gripper can manage to catch a fold or edge in a way that gravity helps keep it taut, it might require surprisingly little force to keep hold. Robots could plan grasps that are "force-efficient" by utilizing fabric geometry (like hooking onto a button or corner). This needs integration of planning and gripper design: a synergy between how the robot handles the cloth and the gripper's capabilities.

In addition, there is a challenge in the durability and maintenance of soft grippers. Soft materials can wear or tear, and sticky surfaces like electroadhesives can accumulate dust and lose stickiness – requiring cleaning (which if frequent, indirectly increases downtime and energy overhead). So materials science plays a role: developing coatings for grippers that resist fouling, or self-clean.

The push for energy efficiency also aligns with Europe's sustainability goals – robots that consume less power are beneficial in factories aiming for low carbon footprints.

4 EU Capabilities and R&D Trends in RTM

Europe boasts a robust ecosystem of research institutions, industry players, and collaborative frameworks that have been actively involved in RTM-related R&D. Over the past decade, the European Union has **strategically funded projects** to push the frontiers of what robots can do with textiles and other deformable objects. This section outlines Europe's capabilities and key R&D trends, highlighting major projects and developments, especially in the Horizon 2020 and Horizon Europe periods.

4.1 Horizon 2020: Laying the Groundwork (2014–2020)

Under Horizon 2020, RTM was primarily championed within the "Leadership in Enabling and Industrial Technologies" pillar, particularly through the **Factories of the Future (FoF)** public-private partnership. A pivotal moment was the 2018–2019 call *"DT-FOF-12-2019: Handling systems for flexible materials"*, which recognized that *"current robots mostly handle rigid objects... What happens in sectors where soft, flexible items require a gentle grasp and adaptive movements?"*. Four consortia were funded from this call, each tackling RTM from different angles:

- **MERGING** (Manipulation Enhancement through Robotic Guidance and Intelligent Novel Grippers, 2019–2023): A €7.6 million project coordinated by CEA (France), MERGING's hallmark was developing a **turnkey robotic solution** for flexible and fragile object handling [30]. It delivered a novel electro-adhesive gripper with a soft "skin" that conforms to delicate items (like fabrics) without damaging them, increasing grip force without heavy clamping. MERGING integrated this gripper with perception and AI-based control to adapt in real-time, aiming for a system accessible to non-expert operators. Significantly, it demonstrated its tech in three sectors: lingerie fabric handling, composite fiber layup, and plastic food pouch handling. In the textile pilot, two robot arms at lingerie maker *Selmark* in Spain collaboratively de-stacked and transferred delicate lace fabric pieces using electro-adhesion, tasks previously done entirely by hand. MERGING showed that such automation could work in real factories, hinting at re-shoring potential in alignment with its funding objectives. As the technical manager stated, *"robots are now capable of proficiently and repeatedly handling deformable objects... revealing new opportunities for European industries"*. The project also didn't shy from broader issues: it noted that after technical feasibility, factors like **technology acceptance, cost-effectiveness, and updated legislation** become critical for adoption [45].
- **REMODEL** (Robotic tEchnologies for the Manipulation of cOmplex DeformablE Linear objects, 2019–2023): Coordinated by University of Bologna (Italy), REMODEL addressed deformable *linear* objects – essentially cables and wires, which are closely related to textile manipulation (think of threads or flexible piping). While not about fabrics per se, it dealt with robotic routing of wiring harnesses in manufacturing – a task analogous to handling limp strings or bands, often done in car or appliance assembly. REMODEL's motivation was explicitly to **ensure Europe can compete with countries having large labour forces** for such tasks [31]. The project built on prior work (FP7 project "WIRES") and created a dual-arm robot system to route and insert cables, demonstrated in four industrial use cases (automotive wire harnesses, aerospace wiring, switchgear wiring, and

medical tube assembly). The theme resonates with textiles: highly repetitive, dexterous tasks moving out of Europe due to labor cost were brought into focus for automation. REMODEL underscored that without automation, activities like wiring harness production had moved outside Europe, citing *"high labour cost and repetitiveness causing high stress"* on human workers. Thus, it framed RTM (broadly speaking) as essential to keep certain manufacturing jobs local and to improve worker conditions. The results from REMODEL contribute techniques applicable to flexible strand manipulation (relevant, for instance, to handling yarns or drawstrings in garments).

- **SOFTMANBOT** (Advanced RoBOTic Technology for Handling SOFT Materials in MANufacturing Sectors, 2019–2023): As the acronym suggests, this project had a broad scope on soft material automation in labor-intensive sectors. It was **end-user driven**, involving industrial partners from four sectors: toy manufacturing, textile/apparel, footwear, and tire production [27]. SOFTMANBOT took a holistic approach, developing a generic **perception–planning–gripper** platform:

  - *Perception* not just of the product (the material) but also the human co-worker, enabling safe HRI (Human-Robot Interaction).
  - *Multi-sensor planning/control* with advanced algorithms (shape servoing, contact control, AI for task generalization) to adapt to the material's behavior in real time.
  - *Smart dexterous grippers* integrating tactile sensors to detect contact with the soft material and adjust grip accordingly.

  The emphasis was on **collaborative robots (cobots)** working alongside humans to boost productivity and job quality, with an explicit goal to *"bring back production to Europe"* by alleviating the drudgery and inefficiency of manual handling. Pilot demonstrations included a textile case (perhaps handling fabric pieces or garments), as well as manipulating soft toys, shoe parts, and rubber for tires. By focusing on multiple sectors, SOFTMANBOT sought to produce *modular, reconfigurable solutions* rather than one-off machines. This aligns with a trend in EU robotics: creating **platform technologies** that can be adapted to various applications, thus benefiting a wider industry base. The project's conclusion envisioned a *"paradigm change where handling of soft materials with robots becomes a feasible and widespread alternative for European factories, especially SMEs"* – an ambitious vision reflecting the EU's wider digitalization goals for even small manufacturers.

- **APRIL** (multipurpose robotics for mAniPulation of defoRmable materIaLs in manufacturing processes, 2020–2024): Slightly later in start, APRIL aimed at **market-oriented, low-cost, multipurpose robots** for semi-automatic tasks in any industry using flexible materials [28]. It leveraged fine grasping, advanced computer vision, sensor fusion, and IoT connectivity (cloud-based knowledge base) to give robots more autonomy and flexibility. Importantly, APRIL included **six real-world demonstrators** across Europe in different domains, e.g. handling paper materials, raw meat (chicken breast), shoe insoles, "viscoelastic" textiles, and cables. This spread highlights that RTM techniques are cross-cutting: solutions for one flexible material can often inspire another. APRIL's use of a *federated cloud approach* for knowledge sharing between robots is a forward-looking idea, indicating European researchers are thinking about how multiple robots could share data (for example, about how to handle a new fabric type) to accelerate learning. By focusing on safety and ergonomics, APRIL also touched on the human factor – suggesting that introducing these robots can improve worker health by taking over strenuous tasks [23]. The project anticipated **productivity and quality gains** leading to greater competitiveness for European industry.

Beyond these four, other H2020 projects indirectly advanced RTM-relevant knowledge. For example, **SMART** and **SOMA** worked on soft robotic grippers and manipulation; **CLOTHILDE** (an ERC grant) studied cloth manipulation foundations; and **MAGIC** focused on handling composite fabrics for aerospace. Also, earlier FP7 projects like **CloPeMa (Clothes Perception and Manipulation, 2012–2015)** were pioneering efforts – CloPeMa built a bimanual robot for cloth manipulation and even showcased automated folding of garments. These set the stage, creating a knowledge base that H2020 projects could build on.

A noteworthy aspect of Europe's approach is **community-building**. The projects above didn't operate in isolation; they often clustered together for knowledge exchange. For instance, MERGING participated in a "Hybrid Production Systems" cluster with other flexible material projects to share progress and challenges. This collaborative ethos is reinforced by euRobotics (the European robotics association) and events like the European Robotics Forum, where special interest groups on manufacturing and soft robotics converge. The result is a fairly tight-knit European RTM research community that spans academia and industry.

4.2 Horizon Europe: Scaling and Integrating (2021–2025)

Horizon Europe has taken the torch from H2020 with an even stronger emphasis on impact, industrial uptake, and twin digital-green transition. Post-2020, the landscape shows **continuity with expansion**: many H2020 efforts led to follow-ups or new projects in Horizon Europe, and new initiatives address gaps such as networking and fundamental science.

Key Horizon Europe developments related to RTM:

- **ADRA & Made in Europe Partnerships:** The "AI, Data and Robotics" (ADRA) partnership and the "Made in Europe" partnership (for manufacturing) guide much of the funding in Cluster 4 (Digital, Industry, Space). Their strategic agendas include goals directly relevant to RTM. For example, the **Made in Europe SRIA** (Strategic Research and Innovation Agenda) emphasizes highly flexible and agile production systems that can handle varying products and materials. A 2021 call, *"AI-enhanced robotics systems for smart manufacturing"*, and a 2022 call, *"Highly flexible and near real-time production lines"* (Twin-Transition 01-04), implicitly cover RTM by seeking robots that can quickly adapt to new product types. Although not textile-specific, these calls fund projects like **HARTU** (Handling with AI-enhanced Robotic Technologies for flexible manufactUring) which address advanced part handling and could be applied to garments. Thus, Horizon Europe is funding enabling technologies – advanced AI for robot adaptation, cognitive mechatronics, etc. – that will benefit RTM.

- **TWINNING and NoE projects:** Recognizing that some EU member states were less involved in robotics R&D, Horizon Europe's widening instruments have supported projects to boost excellence. One such project is **ROMANDIC** (2023–2025), a Twinning project connecting Jožef Stefan Institute (Slovenia) with KIT (Germany) and IRI-CSIC (Spain) to build a *Network of Excellence in Robot Manipulation of Deformables.*

ROMANDIC's aim is to create a roadmap and community for deformables handling, acknowledging that *"there is still no working robot setup capable of effectively manipulating deformables at near industrial levels"*. It's as much about knowledge exchange and capacity building (especially for Slovenia's JSI) as about technical R&D. By bringing in policymakers and industry to their workshops, ROMANDIC is helping align research directions with practical needs and future funding priorities. Additionally, in the euROBIN European network (JSI and KIT are partners) that aims to advance in general robotics components with a focus on reproducibility, some efforts are also devoted to RTM.

- **Fundamental research (ERC and others):** European researchers continue to secure European Research Council (ERC) grants for cutting-edge research that underpins RTM. For example, an ERC project "**CLOTHILDE**" (led by Carme Torras) advanced mathematical representations of cloth states and planning algorithms. Horizon Europe has instruments like EIC (European Innovation Council), which might fund high-risk/high-reward ideas (e.g. new soft robotic actuator concepts or AI for self-learning robots) that could revolutionize RTM. Additionally, the Marie Skłodowska-Curie Actions are training new PhDs in relevant fields, e.g. the *SOFTWEAR* MSCA network on soft actuators for wearable robotics is indirectly related, since that knowledge of soft material actuation can circle back to manipulation.

- **Digital Europe Programme & Testbeds:** Parallel to Horizon Europe, the EU's Digital Europe Programme and national recovery plans (post-COVID) have allocated funds for digital innovation hubs and testbeds in manufacturing. Some textile regions (like Italy's Prato district, or regions in Portugal) have digital hubs focusing on Textile 4.0. These often include demonstrators for automation. For instance, there are pilot lines for digital sewing or automated cutting being set up with EU aid, which complement Horizon Europe's research with on-the-ground experimentation.

- **European Partnership for Textiles (Textiles of the Future):** 2025 will see the launch of a co-programmed European Partnership specifically for textiles [35]. While its primary goals are sustainability and circular economy (reducing waste, recycling, innovative materials), it inherently supports *innovation in production processes*. Crucially, the Partnership provides a framework to advance automation across the entire textile lifecycle—from precision cutting and sewing, efficient handling, to automated sorting, disassembly, and recycling—supporting closed-loop and smart processes. Automation and digitization are pillars to achieve sustainable textile production (e.g. reducing waste through precise automated fabrication) [100]. This partnership, co-led by the Textile ETP and the European Commission, signifies a strong policy commitment to modernizing the textile industry. It will spawn calls in Horizon Europe Work Programmes 2025–2027 targeted at textiles – we can anticipate topics like "Advanced manufacturing for sustainable textile products" where RTM and automation for recycling and reverse logistics will play a key role. The Partnership's Strategic Agenda (released in 2024) likely emphasizes **technology adoption** as crucial for a competitive and green European textile sector [35].

- **Integration of AI and Robotics:** Horizon Europe reinforces the integration of AI with robotics. Projects often involve developing AI modules that allow robots to **learn** how to handle new fabrics or **sense** quality. For example, an ongoing Horizon project **ACROBA** (AI-enabled robotic platform for BAAM) deals with AI in manufacturing robotics. The emphasis is on adaptability: future textile robots should, for instance, be able to handle an unseen fabric type by leveraging prior data or simulation.

- **Standardisation and Ethical AI:** The EU also cares about standardisation (for interoperability) and ethical aspects of AI & robotics (transparency, safety). Though these are horizontal issues, they apply to RTM. We may see Horizon Europe support the development of **standards** for interfaces between sewing machines and robots, or safety norms for human-worker and robot collaboration in sewing lines.

In terms of European capabilities, it's not just projects but also the concentration of expertise, both in academia and industry. Europe has several world-renowned hubs of excellence and industrial providers. In Sec. 6 we will see them in detail.

R&D Trends emerging from all this include:

- A move from *prototype to product*: We see startups or spin-offs coming out of EU projects (e.g. *Robotextile GmbH* emerged from a German initiative, *OmniGrasp* from MERGING to market the electro-adhesive gripper).
- Focus on *SME-friendly automation*: many projects emphasize low-cost and ease-of-use (APRIL explicitly mentions low-cost robots , MERGING aimed at non-specialist-friendly programming).
- *Human-robot collaboration*: Europe tends to favour solutions that don't replace the human entirely but rather automate the worst tasks and let humans focus on higher-level tasks (as per SOFTMANBOT and many policy documents). The idea of the *augmentation* of workers (a robot handling pieces, a human doing fine adjustments or supervision) is prevalent.
- *Application diversity*: While initial efforts might focus on one use case, more recent ones build general frameworks to handle many materials, acknowledging that a flexible robot that can switch between product lines is ideal for Europe's largely small-batch, high-variety production environment.

In summary, Europe's RTM capabilities in R&D are **world-leading** in many respects – European labs produce a large share of the global publications on robotic cloth manipulation, and EU-funded projects have delivered groundbreaking demonstrators. The trajectory from Horizon 2020 to Horizon Europe shows a maturation: from proving concepts (can a robot handle a piece of fabric?) to integrating those concepts into broader manufacturing systems and addressing non-technical aspects like usability, standards, and business models. The next section will connect these R&D efforts to **socio-economic trends**, examining *why* Europe needs to invest in RTM and how societal needs are shaping the research agenda.

5 Socio-Economic Drivers for Textile Automation in Europe

The push for robot textile manipulation in Europe is not happening in a vacuum, it is largely motivated by powerful socio-economic forces. This section maps the key trends in demographics, labor markets, economic pressures, and sustainability that both necessitate and incentivize greater automation in the textile and apparel sector. Understanding these drivers is crucial to gauge the urgency and direction of RTM adoption. In essence, Europe faces a convergence of challenges: an aging skilled workforce, high labor costs, the need for supply chain resilience (highlighted by global disruptions), environmental mandates to make textiles circular, and evolving consumer preferences (like fast delivery and customization). These drivers form the *demand side* of the equation that justifies the *supply side* efforts (the technologies and policies discussed in other sections).

5.1 Labor Shortages and Demographic Shifts

One of the clearest drivers is the **shortage of skilled labor** in textile and garment manufacturing across Europe. The workforce in this sector is aging – many experienced seamstresses, pattern cutters, and machine operators are retiring (especially the Baby Boomer generation), and too few young workers are entering these roles. In part, this is due to the industry's diminished image and competition from other careers; as Prof. Thomas Gries observes, *"the textile and apparel industry has lost its image to biotech and computer science"* in the eyes of young talent [52]. The result is a skills gap: even when companies want to produce locally, they struggle to find workers with the necessary skills or willing to perform repetitive sewing tasks.

Automation is seen as a key solution to this impending labor crisis. If robots can take over the menial and strenuous tasks, the sector can manage with fewer human workers, ideally redeployed to higher-value activities (like supervision, design, maintenance). This is not just theory; several European manufacturers have explicitly cited labor shortages as a reason to automate. A technical seminar by the German Textile Academy bluntly states: *"Automation offers an answer to the increasing labor shortage... it helps secure production sites"* [99]. The Munich Fabric Start event in 2023 similarly noted that labor shortages (along with cost pressure) mean *"the textile industry urgently needs to catch up"* in automation [80].

The situation is compounded by Europe's **demographic trend of an aging population**. Younger Europeans have shown less interest in industrial jobs; many such jobs were offshored anyway in the past decades. For certain highly skilled craft roles (e.g. pattern sewing), there is simply a limited pool of experts left. Without automation, European textile manufacturing could face irreversible decline as the current workforce ages out. In Prof. Gries' words, for Europe's apparel industry it's *"now or never"* to invest in automation if they are to remain competitive by 2030 [52]. He further warns that companies not automating *"will not be competitive by end of the decade"*, implying that the labor scarcity will hit a breaking point.

Labor shortages are not uniform across Europe; they're most acute in high-wage countries of Western Europe and less so in some Eastern European countries that still have garment factories (like Romania or Bulgaria). However, even Eastern European firms report difficulties attracting younger, skilled workers, as many move to other sectors or migrate to higher-paying countries. Thus, automation is of interest even where wages are lower, because finding any workers is becoming a challenge.

5.2 High Labor Costs and Competitiveness

Closely related is the driver of **labor cost**. European labor, especially in Northern and Western countries, is expensive relative to Asia. Manufacturing clothing in, say, Germany or France is far costlier than in Bangladesh or Vietnam when done manually. This cost differential drove offshoring in the first place. Automation presents a way to *decouple production from labor cost*: if machines do most of the work, the cost gap between producing in Europe versus Asia can narrow significantly [77]. SoftWear Automation famously claimed their Sewbot lines could make a T-shirt in the US for under $0.33 labor cost, roughly matching Asian factories [94] (though this figure can be debated, it illustrates the aim).

European manufacturers see automation as a means to achieve **cost competitiveness** while keeping production local. The founder of Robotextile, Michael Müller, points out that in conventional textile plants, *"extremely simple fabric-handling tasks account for about 40% of personnel costs"*, often monotous and tiring work. Automating those tasks can dramatically cut labor costs per unit. His colleague Michael Fraede adds that such automation enables onshore production with *"lower personnel requirements"* yet *"reliable, consistent quality"*, yielding long-term competitive viability [66]. This is precisely the advantage Europe needs to justify local manufacturing: consistent high quality (which European brands demand) at manageable cost. In fact, quality is a key point – automation can reduce the subtle defects and variability that come with manual work, which is valuable for premium segments.

There's also an element of **resilience in cost**. Wages in traditional low-cost countries are rising – e.g. China's manufacturing wages grew 2̃50% since 2005 [98]. While European wages are still higher, the gap is closing. Countries like Romania or Turkey have also seen wage increases. If Europe can automate, it not only deals with its own high wages but also stays ahead of the curve as the rest of the world becomes pricier too. In other words, automation could leapfrog Europe into a position where it can produce at costs comparable to future global averages. This perspective is often expressed by industry strategists who say Europe shouldn't aim to compete with today's low-cost labor, but rather prepare for a future where automation is ubiquitous and those labor advantages diminish.

However, it's important to note that labor cost reduction via automation comes after *significant capital investment*. The socio-economic equation must consider the **capital expenditure vs. labor savings**. Large companies with capital (like automakers) have automated heavily; the garment industry, being low-margin, has historically shied away from heavy capital spending, especially SMEs. One barrier is the *high initial investment* of automation, cited by industry sources as a challenge [98]. Socio-economically, if Europe wants to encourage adoption, policy incentives or financing support might be needed so that the long-term macro benefit (competitiveness, jobs saved) justifies short-term costs to companies.

5.3 Re-shoring, Supply Chain Resilience, and Strategic Autonomy

The concept of **re-shoring** (bringing manufacturing back to Europe) or **near-shoring** (shifting it to closer countries like those in North Africa or Eastern Europe) has gained traction. Several drivers feed into this:

5.3.1 Supply chain disruptions

Events like the pandemic, Suez Canal blockage, or geopolitical tensions have highlighted risks in long, overseas supply lines [98]. If critical production (even of basic goods like masks or uniforms) is entirely abroad, Europe can be caught short in crises. By automating, production can be economically done onshore, ensuring a measure of self-sufficiency. This ties into the EU's broader goal of *"open strategic autonomy"*, the idea that the EU should have the capacity to produce essential goods domestically for resilience. The early pandemic scramble for PPE made very visible the downsides of 100% offshore dependency. Subsequently, we saw many European firms and projects receive support to create onshore mask and gown production lines (some automated, some semi-automated). These are perhaps small footprints, but they set precedents.

5.3.2 Faster response and customization

Fast fashion and e-commerce have conditioned consumers to expect rapid turnaround. Local automated production can deliver small batches quickly to European markets (no 4-week shipping time from Asia), enabling agile response to trends and even **customized production**. Consumers are also increasingly interested in **made-to-order** or personalized garments; robots can make one-off productions more feasible. As a result, reshoring is not just about cost but also about **speed-to-market**. A shirt made in Europe can go from production to store in days, versus weeks from Asia. This is crucial for certain sectors (sporting event merchandise, quick fashion capsules, etc.). Texspace Today notes *"localized production can enable just-in-time manufacturing and on-demand production"*, aligning with consumer demand for speed [98].

5.3.3 Trade and tariff factors

Unpredictable trade policies (e.g. US-China trade war, EU's potential carbon border taxes) make overseas sourcing costlier or riskier. Some companies have re-shored to avoid tariffs or reputational risks. For example, Hong Kong's Esquel Group invested in robot-enabled shirt factories to offset US tariffs by producing closer to the market [96]. While that's Asia-to-US, similar logic can apply EU-internally if trade dynamics shift (e.g., if carbon footprint costs increase for imports, local production becomes relatively more attractive financially). Europe is considering measures like extended producer responsibility, which could effectively penalize long-distance outsourcing if it's seen as externalizing environmental costs.

5.3.4 Strategic sectors

Certain textile products are of strategic importance, e.g. military apparel, medical textiles. Europe may not want to rely on imports for these. Automation could rebuild capacity in these niches. RTM in technical textiles (like 3D weaving of composites for aerospace) is also strategic; Europe leads in some of these, and further automation secures that lead.

Europe's policy documents often mention textiles in the context of *strategic autonomy and resilience*. The new European Partnership for Textiles explicitly aims to *"strengthen Europe's leadership"* and global competitiveness in textiles [35]. Part of that leadership is having manufacturing capability, not just design. The partnership notes the need for *"cost-competitive production practices"* – which implies automation. Moreover, the *EU Strategy for Sustain-*

able and Circular Textiles (2022) calls for innovation to make supply chains shorter and more sustainable, implicitly supporting local, tech-driven manufacturing [35].

Real examples in Europe reflect re-shoring attempts: as cited earlier, C&A's pilot to bring jeans production from Asia to Germany with automation is a prime case [66]. In Spain, some companies in high-end fashion are exploring small automated ateliers. In Eastern Europe, firms hope robotics can help them keep business that might otherwise move to cheaper countries.

The Texspace Today analysis highlights that re-shoring via automation is plausible but comes with *challenges* (investment, skills, etc.) [98]. Still, many fashion executives (67% in McKinsey's The State of Fashion 2023 survey [78]) plan to increase near-shoring because of recent shocks. Automation is *"at the heart of reshoring efforts, offering solutions to traditionally labor-intensive processes"*, mentions Adidas' Speedfactory as an example of robotics enabling local production (even though Speedfactory ultimately moved to Asia, it proved the concept technologically) [98].

5.4 Sustainability and Circular Economy

Sustainability is a cornerstone of EU socio-economic policy (e.g. the Green Deal), and the textile industry is under heavy scrutiny for its environmental impact – from water use and pollution to waste and carbon emissions due to global transport. Automation can contribute to sustainability in several ways:

5.4.1 Localized Production = Lower Emissions

Producing closer to the consumer cuts down on long-distance shipping, thus lowering the carbon footprint of a garment. A shirt made in Europe instead of being shipped from Asia saves fuel. Also, "made-to-order" production prevents overproduction and excess inventory, which often ends up as waste. As Texspace noted, *"sustainability-conscious consumers prefer domestically produced garments to reduce carbon footprints"* [98]. Reshoring with robots thus aligns with green consumer expectations and emerging "carbon accounting" that companies must do. It's worth noting that the fashion industry's logistics (shipping millions of tons by sea and air) is a non-trivial contributor to emissions. By automating, Europe can viably shorten those supply chains.

5.4.2 Precision and Waste Reduction

Automated cutting and fabric handling can optimize material usage. For instance, automated cutting machines (already common) with AI nesting algorithms reduce fabric scrap. In sewing, if robots can tightly control seam allowance and placement, they might reduce defects or the need for generous tolerances, saving material. Also, fewer mistakes means less waste: AI vision can detect fabric flaws or mis-stitches early, preventing whole batches of product from being scrapped [86].

5.4.3 Recycling and Sorting

RTM also plays a pivotal role in the circular economy aspect – automated sorting of used textiles for recycling (using AI vision to identify fabric types) and even automated disassembly of garments. Siptex's world's first large-scale automated textile sorting plant [74] or recent

EU innovation challenges are targeting this. Another example is Cetia, the French company using AI and robotics to disassemble specific garment components using laser [60]. Improved RTM means a robot could one day flexibly deconstruct a garment into parts for recycling or repair. This aspect ties directly to EU policies mandating textile waste recycling: by 2025, all EU states must separately collect textiles [41], which will flood the system with used textiles needing processing. Automation is likely the only feasible way to scale up sorting and recycling to handle that volume cost-effectively.

5.4.4 Ethical and Safe Production

Sustainability in EU discourse includes social sustainability and fair labor conditions. By automating the drudgery, Europe can ensure any remaining jobs in textile manufacturing are higher-skilled, safer, and better-paying. It avoids the ethical issues of sweatshops and child labor that taint global fashion supply chains. In fact, new regulations like the German Supply Chain Act compel brands to ensure ethical production; one way to guarantee no labor exploitation is to produce in automated European facilities under EU labor laws. Jürgen Mohs of C&A noted reshoring with automation *"takes place under ethically fair conditions – increasingly important in context of the new Supply Chain Act"* [66]. This is a selling point: "robot-made in Europe" can imply no exploitation. It might even become part of branding (some brands already advertise items as made with "3D knitting technology in the EU" to highlight tech and ethics). Thus, RTM can help brands meet due diligence requirements for labor standards by reducing reliance on complex global subcontracting chains.

5.4.5 Innovative Sustainable Materials

Europe leads in developing bio-based or smart textiles. Many of these new materials (e.g. biodegradable fabrics, composites with natural fibers) may require new handling techniques. Automation capabilities will be important to process these novel materials at scale. The new Textile Partnership is explicitly linking digital innovation with sustainable textiles [35], envisioning modern factories that can handle tomorrow's eco-friendly materials, which might be more delicate or different in behavior (for instance, recycled fibers might be shorter, requiring careful handling).

There can be some tension between sustainability and automation: robots consume energy, and building robotic equipment has its own environmental footprint. But overall, studies (like IEA's note in the dark factory article) suggest industrial automation can reduce energy use by optimizing operations (estimated 15-20% energy savings in some cases) [33]. For example, robots can run processes at night when energy is abundant and cheap, smoothing energy demand. Or they can precisely control heating in dyeing processes to avoid overshoot. Also, if properly managed (and powered by renewable energy, as many European factories aim to be), automated textile production can be more sustainable than current practices that involve wasted inventory and inefficient use of resources. A simple case: overproduction is a huge waste issue (billions of garments are unsold each year and often destroyed). On-demand production via automation could slash that waste, meaning the overall environmental impact is lower even if a bit more energy is used in manufacturing per item (due to robotics) – because you simply make fewer unnecessary items.

In summary, **sustainability drivers** push RTM by aligning the technology with Europe's environmental goals and consumer values. From lowering emissions through local production to enabling recycling and eliminating unethical labor, automation supports a **more circular and responsible textile industry**. This is reflected in both EU policy (e.g., the mention of automation in the circular textile strategy) and in market trends (premium consumers willing to pay for "clean" products). It's a fortunate convergence: the same technologies that can make Europe competitive (robots, AI) also can make it greener and fairer.

5.5 Consumer Trends and Market Dynamics

European consumers are increasingly drawn to product attributes that RTM technologies can help deliver. One notable trend is the growing demand for customization. The combination of online ordering platforms and advances such as 3D body scanning has created fertile ground for custom-fitted clothing delivered within days. While traditional custom tailoring remains costly and time-consuming, robotic manufacturing opens the door to semi-custom garments produced at prices comparable to off-the-rack options. This convergence of personalization and efficiency represents a promising socio-economic niche—mass personalization—that aligns well with Europe's affluent and quality-conscious markets. Already, companies like Nike offer custom shoes via automated knitting, and start-ups in Europe (e.g., Unmade in the UK) use software to allow individual designs to be knitted on demand. RTM would amplify this by extending such capabilities to sewn garments, not just knitwear. Consumers benefit from uniqueness and perfect fit; the European industry benefits by differentiating products and potentially charging premium prices, which can offset higher production costs.

Another dynamic shaping the market is the emphasis on quality and innovation, particularly within Europe's high-end and luxury segments. These brands rely heavily on craftsmanship and precision, areas where robotics can potentially excel. Automated production lines with advanced sensors and control systems could reduce errors such as misaligned seams or inconsistent stitching, issues that often stem from manual fatigue. Furthermore, RTM technologies might unlock entirely new design possibilities, including complex 3D-knitted structures or ultra-fine constructions beyond human dexterity. In this context, the phrase "made by robots in the EU" could evolve into a distinctive mark of technical excellence, craftsmanship, and innovation. Luxury players, while publicly emphasizing the handmade aspect, are quietly interested in how automation can improve consistency (luxury customers have zero tolerance for defects) and relieve their artisans from tedious tasks (like basic assembly) so they can focus on decorative work. We see hints of this: LVMH and Kering both invest in textile tech R&D [62, 88].

Finally, the "Made in Europe" label continues to carry weight among consumers who associate it with ethical standards, traceability, and superior quality. There is a growing willingness to pay a premium for products that are locally and responsibly manufactured. If automation reduces the cost differential between European and offshore production, more brands could feasibly offer EU-made lines tailored to this consumer segment. This is not only a market opportunity but also a reflection of broader socio-cultural currents—such as renewed pride in local production and sustainable industrial practices. It dovetails with the sustainability points above: a segment of consumers (especially in Europe) actively seeks out domestically produced items, equating them to fewer environmental miles and guaranteed fair labor. RTM lowers the barrier for brands to satisfy this segment without pricing themselves out of the market. For instance, a mid-range brand might introduce a "Made in Europe" capsule collection produced in an automated micro-factory, testing consumer appetite, and find that demand is strong and brand image is enhanced.

In essence, consumer trends in Europe (and similar developed markets) are creating a **pull factor** for RTM. They want speed (fast fashion timing but with sustainability), personalization, quality, and ethical assurance. Traditional manufacturing struggles to deliver all of these simultaneously, as it could deliver cheap and fast, but then often fails on ethics or personalization. RTM promises a scenario where **"fast, good, and fair"** can coincide. The socio-economic implication is that those companies that adopt RTM can better meet these modern consumer demands, potentially capturing market share and commanding higher margins. It's a driver that complements the cost push: even if RTM were cost-neutral, the market-side benefits of agility and customization could justify it.

5.6 Economic Feasibility and Industrial Structure

From a macro-economic view, Europe maintaining a **textile manufacturing base** has benefits: preserving jobs (even if fewer, they'll be higher-skilled), balancing trade, and being at the forefront of textile innovation. Europe still has world-leading textile companies (in technical textiles, high-quality fabrics, etc.), and they argue that having production close to R&D speeds up innovation. For example, advanced functional textiles often require iterative prototyping which is easier when production is local. The EU27 records the highest number of industrial designs' applications filed in TCLF[1] sectors according to the latest Euratex report [36].

Opponents might point out that if automation becomes universal, those same robots could be deployed anywhere in the world. True, but Europe's edge could be in the integration of the whole value chain: design, robotized production, quick distribution, and in building the most advanced automated plants and exporting such technology. In other words, Europe could become both a producer of high-end textile goods *and* the machinery and software that power the world's automated factories. We see initial signs of this: European firms like **Lectra, Jakob Müller, Stäubli** etc., who make textile machinery, are increasingly incorporating robotics and selling these globally. If Europe invests now in RTM, it can own the IP and standards, making its approach the global norm (similar to how German companies defined a lot of automotive automation tech).

Also, the European Commission is invested in **manufacturing as a pillar of the economy**. Reinvigorating a sector like textiles through technology aligns with wider economic strategies to avoid over-reliance on imports and to create tech-driven jobs outside of just the service sector. Europe's textile sector is mostly SMEs, which have limited capacity to invest in risky technologies individually. But collectively, via clusters and EU programs, they can pilot innovations. Many of the drivers above (labor, sustainability, etc.) are felt acutely by SMEs. If EU initiatives and funding lower the risk, these SMEs can adopt RTM – potentially transforming an industry that was considered sunset into one that's high-tech. This aligns with EU strategies like Industry 5.0 (human-centric, sustainable, and resilient industry vision), where technology upgrades in traditional sectors are encouraged.

Europe's socio-economic landscape creates a **strong impetus** for RTM: An aging workforce and shortage of sewing skills push for automation to keep production viable; high wages push for robotics to cut per-unit labor input; desire for supply chain resilience and autonomy encourages bringing production closer, which is only feasible via automation; sustainability goals align with tech-enabled local, efficient manufacturing; and evolving consumer preferences open new avenues that automated local production can exploit. These drivers have been explicitly

[1]TFCL: Textile, footwear, clothing and leather

recognized by experts and policymakers – as evidenced by quotes like *"we have to look for skilled workers and I believe automation and robotics has a big opportunity to help"* [52], and events like "Robots in Textile Industry – how automation can secure jobs in Europe" [80]. Europe's research and innovation agenda in RTM is thus shaped not just by the allure of cool technology, but by tangible socio-economic needs. The next section will examine the key actors responding to these needs and how their activities reflect the intersection of technology and socio-economic strategy.

6 Key Actors and Case Studies

The advancement of robot textile manipulation in Europe is being driven by a diverse set of actors across the research, industry, and policy spectrum. In this section, we map out the key players, from cutting-edge research groups to pioneering companies and influential policy bodies. We also highlight specific case studies and real-world demonstrations that illustrate these actors' roles and the progress being made. The ecosystem is truly multidisciplinary: it involves robotics experts, textile engineers, entrepreneurs, fashion brands, and government agencies all interacting. Europe's relatively collaborative innovation culture (through EU projects, clusters, and associations) means many of these actors are interconnected, often working together on consortia or pilot projects.

6.1 Research Institutions and Academia

Europe's rich academic landscape forms the backbone of RTM research. Several institutes and universities have dedicated teams tackling the challenges of deformable object manipulation:

- **Institut de Robòtica i Informàtica Industrial (IRI), Barcelona, Spain:** A joint CSIC-UPC center, IRI has a *Robot Perception and Manipulation* group with a strong track record in cloth manipulation. Led by Prof. Carme Torras (a prominent figure who has led multiple EU projects), the group has worked on aspects like **grasping primitives for cloth, cloth state estimation, and learning algorithms for folding**. They were involved in projects like CLOTHILDE [29] and are partners in Horizon projects (e.g., ROMANDIC [38], SoftEnable [32]). IRI's contributions include state representations to understand garment manipulations, planning algorithms, accurate simulators, and benchmarking methods. Prof. Torras is also known for bridging robotics with ethics (she wrote about robots in care and daily tasks in fiction and essays), which adds a dimension to how they approach human-robot collaboration in tasks like dressing.
- **Deutsches Zentrum für Luft- und Raumfahrt (DLR) – Institute of Robotics and Mechatronics, Germany:** DLR is one of the world's top robotics labs, and although known for aerospace and industrial robotics, it has played a role in RTM-focused efforts (like the EU project SOMA on soft manipulation [25]). DLR developed the sensitive lightweight arms (e.g., KUKA LBR iiwa originates from DLR's LWR research) that are now used in many collaborative manipulation setups [34]. In SoftEnable, DLR is building a new gripper for deformables in logistic scenarios. Their strength is in high-performance control – crucial when dealing with delicate materials to apply just the right force.
- **Karlsruhe Institute of Technology (KIT), Germany:** KIT's High Performance Humanoid Technologies lab is another key player. They have expertise in perception and have worked on modeling deformable objects. KIT is a core partner in ROMANDIC and brings knowledge from its development of the ARMAR humanoid robot series and its leadership in several EU projects. It has established deep expertise in robotic manipulation, spanning bimanual coordination, human-robot sensorimotor augmentation, and AI-driven grasping in complex environments [61]. Also, KIT's involvement signals Germany's interest via its network in manufacturing research. Karlsruhe's proximity to

textile industry clusters in Baden-Württemberg (like technical textiles companies) also helps test tech in industry settings. They've done demonstrations of bimanual cloth folding and contributed to benchmarks [7].

- **Jožef Stefan Institute (JSI), Slovenia:** Perhaps a surprise entrant, JSI has risen in prominence by leading ROMANDIC. JSI's Humanoid and Cognitive Robotics Lab, led by Dr. Aleš Ude and Dr. Andrej Gams, works on skill transfer and adaptive control. By spearheading a network on deformable manipulation, JSI is elevating its capacity through partnerships with KIT and IRI [38]. This reflects the EU's effort to spread expertise to newer member states (widening). JSI's ABR department has a strong foundation in humanoid robotics and robotic perception, and this expertise has been explicitly extended to deformable-object manipulation—most notably through kinesthetic teaching and learning-from-demonstration techniques enabling bimanual cloth handling in human–robot cooperative scenarios.

- **KTH Royal Institute of Technology, Sweden:** KTH coordinates the SoftEnable project [32]. Dr. Florian Pokorny's group (Robotics, Perception and Learning) brings a blend of geometric and machine learning approaches to manipulation. SoftEnable's focus on "soft fixtures" in healthcare and food handling shows KTH's strength in conceptual framework – taking an industrial concept (fixture) and generalizing it to deformables. In parallel, Prof. Danica Kragić, an IEEE Fellow and ERC Advanced Grant recipient for the BIRD project on bimanual manipulation of rigid and deformable objects [26], leads pioneering research on dexterous handling of deformable materials, reinforcing KTH's leadership in foundational robotics for RTM [57]. KTH also looks at human-robot interaction aspects (like how an operator can easily reprogram a cloth manipulation task) [79]. Sweden's strong textile recycling initiatives (Siptex, etc.) also mean KTH is adjacent to that topic.

- **RWTH Aachen University – Institute of Textile Technology (ITA), Germany:** ITA is a world leader in textile engineering. Under Prof. Thomas Gries, ITA has increasingly collaborated with robotics groups to integrate automation in textile processes. They are part of the "Textile Factory 7.0 (T7)" initiative, exploring how a future clothing factory can look [66]. The presence of a traditional textile institute in these collaborations underscores that material specialists and roboticians are working together. ITA contributes deep knowledge of textile processes (sewing, knitting, weaving, finishing) which is crucial to develop robots that truly work in factories –they know the tolerances, the pitfalls that might not be obvious to roboticists (like how fabrics behave in industrial machines) [65].

- **Niederrhein University of Applied Sciences, Germany:** Home to a major textile and clothing faculty, Niederrhein UAS is deeply involved in T7 and in implementing automation in pilot lines, often working with industry in the Mönchengladbach textile region [66]. They contribute applied R&D, e.g., helping design the layout of automated workflow or ensuring textile quality standards are met. Their professors in garment tech and production systems have decades of know-how on what fails in apparel automation (many attempts in the 80s/90s failed; they have that historical perspective). They ensure that new RTM solutions address the right practical problems.

- **Ghent University, Belgium**: Led by Prof. Francis Wyffels, Ghent University is advancing robot textile manipulation through research on perception-driven manipulation of deformable materials. Wyffels's group has developed systems for keypoint detection in cloth using synthetic data, enabling robots to fold and arrange textiles with higher precision [70]. Their work also includes in-depth analyses of cloth manipulation pipelines emerging from robotics competitions, positioning Ghent as a key player in benchmarking and developing robust RTM algorithms.

- **Others:** Many universities across Europe have individual labs contributing, e.g., **EPFL** (Switzerland) worked on electroadhesive gripping (partner in MERGING) [30]; **Aalborg University** (Denmark) on vision for textiles; **University of Cambridge** (UK, pre-Brexit) had work on 3D vision for folding clothes; **Politecnico di Milano** (Italy) on automation for fashion, etc. The network effect of EU projects means these groups often share results.

These academic actors are producing the PhD graduates and knowledge that feed industry innovation. Importantly, many of them engage in **public dissemination**: e.g., they present demonstrations at venues like the European Robotics Forum or Automatica trade fair, raising awareness in industry. They also publish open datasets or open-source code (some projects released cloth simulation datasets, trained models, etc., beneficial to all). This open innovation environment in Europe accelerates progress collectively.

6.2 Industry Players – Automation Providers and Adopters

On the industry side, we consider two categories: those providing the automation technology (robot makers, integrators, startups) and those adopting it (textile/apparel manufacturers, recyclers and brands).

6.3 Automation Technology Providers

- **Robot Manufacturers (KUKA, ABB, etc.):** Europe's industrial robot makers have started highlighting solutions for flexible materials. For instance, **KUKA** published a case study on "small robotics in textile production" featuring Robotextile's system [66]. KUKA provided the robots (SCARA and LBR iisy cobots) and worked with the integrator to fine-tune them for fabric handling. ABB similarly has shown concept demonstrations of robots folding clothes or automated fashion concepts in its research hub. These companies see a market: as textile firms consider automation, they will need robots and these manufacturers want to supply them. By developing domain-specific know-how (like KUKA did with special grippers via partners), they expand their market beyond traditional sectors. Another example is **Bosch Rexroth**, which has an Automation unit that collaborated on a project for automated pillow production.

- **Specialized Integrators and Startups:** One notable startup is **Robotextile GmbH** (Dormettingen, Germany), which emerged to deliver automated handling systems for garment production. Founded by Michael Müller and team, Robotextile developed the aforementioned fabric-layer picking system using KUKA robots [66]. They partnered with apparel firms like C&A to implement it. This shows entrepreneurship from within Europe to commercialize RTM tech. Another is **Sewts GmbH** (Munich, Germany), which is focusing on using robots in industrial laundries – their system "VELUM" automates the handling of towels and linens, addressing labor shortages in laundry services [90]. Sewts' longer-term ambition is garment sewing automation; they have publicly discussed tackling clothing handling step by step. From France, **Lectra** (famous for cutting machines) is investing in automation for sewing rooms, possibly through acquisitions or internal R&D on robot-assisted cutting and kitting. **OmniGrasp** (Zurich, Switzerland) is commercializing the electroadhesive gripper from MERGING – important because if a delicate gripper is on the market, many integrators can use it for various textile tasks.

- **Sewing Machine Companies:** Traditional sewing machine makers (e.g. **Dürkopp Adler** in Germany, **Pfaff Industrial**, **Juki** in Japan with European branches) are also actors. They have been adding automation in limited ways (Dürkopp has automatic sewing stations for specific seams). They now explore collaborating with robotics – for example, a robot could load pieces into a Dürkopp sewing unit. These companies participate in EU projects or industry groups to keep abreast and possibly co-develop solutions. If they reinvent themselves as providers of robotic sewing lines, it secures their future.
- **Vision and AI Companies:** Handling textiles requires good vision; companies like **Cogniac** or **Blue Vision Labs** (UK) that do industrial vision have had pilots in textile quality inspection. **Truetzschler** (a textile machinery co.) and partners achieved an AI-based system for precision fabric inspection, which is tangential but related (it could guide robots to defects). Startups in AI like **Cambridge Consultants** developed a demonstrator of robotic sewing by stiffening fabric (a concept akin to Sewbo, but done in the UK). These highlights indicate a cross-pollination: AI companies find textiles a great testbed for advanced algorithms.
- **Recycling solution companies:** Europe hosts a growing ecosystem of companies pioneering robotic and AI-driven technologies for **textile recycling**. **NewRetex** (Denmark) operates a state-of-the-art automated sorting line that combines NIR sensors, cameras, and AI to categorize textiles by material type, color, and composition, achieving traceable precision at an industrial scale [82]. **Matoha** (UK) has developed pocket-sized, AI-powered NIR scanners capable of identifying fabric composition in under a second—an essential tool for scaling up manual sorting and preparing the ground for future robotic integration [76]. Meanwhile, **Resortecs** (Belgium) offers a unique solution for disassembly: its thermal "Smart Stitch™" threads dissolve at controlled temperatures, enabling automated garment teardown in dedicated ovens—removing trims and seams at speeds up to 5× that of manual methods while preserving over 90% of textile content [85]. These European innovators exemplify the continent's drive to create shorter, smarter, and more circular textile value chains through robotics-enhanced sorting and disassembly.

6.4 Manufacturers and End-Users (Adopters)

- **Textile and Apparel Manufacturers:** In Europe, much of the volume clothing manufacturing has left, but there are still companies in niche or high-end markets and some volume in Eastern Europe. These firms are increasingly testing automation to stay viable. For example *Selmark Lingerie* in Spain, which was a pilot site for MERGING's fabric handling cell [45]. Lingerie has delicate fabrics and small pieces. If robots can handle that, it's a win. Selmark's involvement suggests even medium-sized apparel firms are open to experimenting, given the right support. **Van de Velde** (Belgium, luxury lingerie) is also known to invest in tech to keep production partly in Europe. **VDL Fibertech Industries** (Netherlands) was a composite user in MERGING, but it shows interest from technical textile users in automation [45]. **Freudenberg** (a German textile conglomerate) and others in technical textiles have internal automation projects for things like filter production, where handling non-rigid fibrous mats is needed. In a recent development, **Inditex** has launched an **Open Innovation Logistics Hub**, soliciting startups and research centers to propose intrafactory logistics and automation solutions—showing that even scale-fashion giants are looking to pilot robotics within their operations [54].

- **Brands/Retailers:** C&A's case stands out. C&A, a major fashion retailer, built its FIT factory (Factory for Innovation Textile) in Germany with advanced automation and aiming for 800k jeans/year as a bold move [66]. They cited multiple motivations: speed, sustainability, relearning manufacturing, and supply chain stability. Adidas tried with *Speedfactory* – using cutting-edge 3D knitting and some robotic handling for shoe production in Germany and the US; while those were relocated, Adidas still uses some automated processes and localized production (and the knowledge gained was valuable). Luxury brands like **Louis Vuitton** are also quietly automating certain steps (e.g., cutting leather) to boost throughput in their workshops, although they don't advertise it as "robot-made" as most of the work remains artisanal [8, 81]. They are also investing in intrafactory and warehouse automation [88].
- **Textile Machinery Companies:** Companies that make the machines used in textile factories are crucial actors because they can integrate robotics into their product lines. For example, **Gerber/Lectra** in cutting, **Stäubli** in weaving (they make automatic draw-looms and recently robotic harness change systems). **Italy's textile machinery association** (ACIMIT) promotes Industry 4.0, encouraging Italian machine builders to incorporate AI and robotics to stay competitive. These companies might partner with robotics firms to offer new combined solutions. They have the client base trust, so if they come with a "semi-automated sewing line" product, factories listen.
- **Consortia & Clusters:** In Europe, regional clusters often drive innovation. For instance, the *Techtera* cluster in France (Lyon area) brings together technical textile firms and has projects on automating the production of fiber composites. In Italy's Carpi district (knitwear), there's interest in robotic knitting and finishing. These industry clusters sometimes apply for EU or national grants as a group, acting as living labs. The Catalan cluster AEI Tèxtils participates in the EU-funded HEREWEAR project, which pilots regional microfactories automating parts of bio-based garment production for circular wear [24], while the UK's Textile 4.0 cluster—anchored by Manchester's Robotics Living Lab—deploys collaborative robots for sewing, cutting, pressing, and quality control [103]. In both cases, clusters pool access to advanced automation resources that individual SMEs couldn't afford alone.

Overall, this multitude of industry actors demonstrates that RTM is not just a lab curiosity but is being actively pursued in the field. To further illustrate the state-of-the-art and the interplay of actors, we now present some **case studies and demonstrations** that exemplify multi-actor collaboration and progress.

6.5 Case Studies & Demonstrations:

A few concrete case studies exemplify multi-actor collaboration and the state of the art:

1. **Robotextile & C&A – Automated Jeans Factory:** Already described, this involves a robotics startup, a robot supplier (KUKA), a major brand (C&A), and academic partners (ITA, Niederrhein). It delivered a working pilot line. The system can pick up limp denim panels, align and stack them, and feed them into sewing or laser finishing operations. The achievement was picking single layers reliably, *"a milestone in textile production"*, as they touted. This case underscores that with concerted effort, a notoriously difficult task was solved and put into a real production context. C&A's quote on reshoring benefits (environmental, ethical) and the need to combine sustainable production with productivity sums up the strategic value [66].

2. **MERGING Project Pilots – Lingerie Fabric Handling Cell:** In MERGING's textile use-case, they installed a cell at Selmark in Spain where **two robot arms equipped with electro-adhesive grippers** could pick delicate lace fabric pieces from a stack, present them for quality inspection via vision, and transfer them for the next operation. This replaced manual de-stacking, a tedious task, and did it with the care needed for fine fabric. The success is noted by Christine Rotinat (CEA coordinator), emphasizing that *"some of these technologies can be rapidly applied to industrial applications, at relatively low cost... opening access for SMEs"* [45]. The involvement of an SME like Selmark and a major research body like CEA shows the bridging of scale: innovations are being passed to even family-owned firms. It's a template: demonstrate in a real factory, with training of staff and collecting feedback.

3. **SOFTMANBOT Pilot – Automated Pillow/Footwear Assembly:** While details are sparse, one SOFTMANBOT pilot in the **footwear sector** likely involved handling flexible shoe insoles or uppers. Footwear assembly is still largely manual (cut, glue, last the shoe, etc.), so a robotic assist would be novel. If an operator and robot share tasks (the robot holding and stretching an upper while a human positions it, for example), it can improve ergonomics and consistency. Another pilot on **toys** could mean stuffing toys or stitching, again laborious tasks often done in low-cost countries. These pilots indicate the breadth, not just apparel, but any product with soft materials (plush toys, etc.) is in play [93]. It also signals that the EU expects cross-fertilization: a technique proven in toy assembly might apply to apparel and vice versa.

4. **ARM Institute Projects (USA) – for comparison:** It's useful to note the US ARM projects like "Robotic Assembly of Garments", which stiffened fabrics for robot handling. One deliverable (nicknamed "Bot Couture") used a robot to do a piece of a sewing operation by laminating fabric with a soluble plastic to make it temporarily rigid [4]. While not European, European researchers are certainly aware (these results are published). It provides a different approach. A European company could license or replicate the idea. This highlights a somewhat competitive actor, American startups, but

also an opportunity for collaboration. Indeed, SoftWear Automation (US) and certain Chinese initiatives are external actors that European firms keep an eye on, sometimes partnering via supply chains (e.g., a European brand might beta-test SoftWear's Sewbot).

These case studies highlight that multi-actor collaboration (startup + corporate + university) is a hallmark of Europe's approach, and it is yielding tangible results. We see breakthroughs like reliable single-layer picking or automated sorting of delicate pieces, which were long unsolved.

6.6 Policy Bodies and Industry Associations

Beyond those building and using the technology, several **policy and industry bodies** act as facilitators, advocates, or regulators shaping the RTM landscape:

- **European Commission (DG Research & Innovation, DG GROW, DG CONNECT):** The Commission sets the funding priorities and industrial strategies. They issued the calls that funded the projects above and now are pushing partnerships. Officials like the Executive Vice-President for Industrial Strategy are vocal that initiatives like the textile partnership will *"drive technological progress and sustainability across the sector... accelerate the transition toward a stronger, more competitive and sustainable European textile industry"* [35]. Such high-level endorsement not only directs funding but also encourages industry to co-invest (knowing policy is backing this direction). The Commission also monitors progress: through CORDIS results packs and evaluation of project outcomes, they assess how close we are to goals (like how many companies adopted these technologies, how many patents, etc.).
- **EURATEX (European Apparel and Textile Confederation):** EURATEX represents the European textile & clothing industry. Traditionally focused on trade policy and competitiveness, in recent years, EURATEX has championed innovation as the way forward. They help lobby for the textile partnership and emphasize automation in their publications. For instance, their 2023 press release warned that *"the EU's trade deficit in textiles and clothing has increased to €70 billion"* and implied that without innovation, Europe becomes ever more reliant on imports [55]. EURATEX supports projects (they have been partner or advisors in EU projects on digitalization), and runs the Textile ETP, which is directly co-leading the new partnership. Their messaging often highlights that new technologies (digital, automation) are *essential* for a "resilient, competitive" textile industry [35]. They also coordinate *skills programs* (like the EU-funded Skills Alliance) to retrain workers, acknowledging that as automation grows, workforce skills must shift.
- **EFFRA (European Factories of the Future Research Association):** EFFRA is the private side of the Made in Europe partnership, basically the voice of advanced manufacturing industries in EU R&D. EFFRA was involved in shaping the FoF calls that included RTM. On their website, they've showcased projects like MERGING, highlighting them as success stories that *"robots begin to handle flexible materials opening up opportunities for European factories"* [45]. EFFRA helps disseminate project results and connect project consortia with the broader industry. They also maintain a database/portal of project deliverables, which helps cross-project learning.

- **euRobotics AISBL:** This association between academia and industry covers all of robotics. Within it, there are topic groups like "Agile Production" or "Agriculture and Food" where deformable object handling is relevant. euRobotics co-authored the Strategic Research Agenda for robotics, which under Horizon Europe merged into ADRA. They ensure that funding calls cover robotics challenges such as RTM. Additionally, the **European Robotics Forum (ERF)** annual event often has workshops on manipulation of deformables, bringing together academic and industry folks.

- **National Governments and Initiatives:** For example, **Germany's Ministry of Economy** has funded the "Future of Textile Production" via T7 and other projects. The German government also runs an Industry 4.0 program that includes textile demonstration centers. In France, the Government included textiles in its "Industrial Revitalization" plans for certain regions. Italy's National Recovery Plan has funds for upgrading textile/clothing SMEs with digital tech. Such national support often complements EU funds (e.g., a company might get an EU grant for R&D and a national subsidy to implement a pilot line).

- **Standardization Bodies:** Though early, discussions might start in ISO or CEN about standards for collaborative textile robots, or test methods for automated seam quality, etc. Having European experts lead that would be an advantage, making European-developed methods the global standard.

The interplay of these actors can be summarized in a matrix of roles (as in Table 1, which is conceptual). Essentially, Europe's approach involves stakeholder collaboration rather than letting any one segment drive it alone. This is a strength, but it can also slow things down (consensus-building takes time). So far, it has yielded concrete pilots and a vibrant research community, but widespread industrial adoption is still on the horizon.

Table 1: **Actors' interplay and roles.**

Actor	**Role in RTM advancement**	**Examples of Initiatives/Contributions**
European Commission (Policy level)	Sets R&D priorities, provides funding (Horizon, partnerships); aligns RTM with EU strategies (digital, industrial, green)	FoF & Horizon Europe calls (DT-FOF-12-2019 etc.); Textile Partnership launch; Industrial strategy communications supporting automation.
Research Institutes & Universities	Conduct fundamental and applied research; develop prototypes; train talent	IRI-CSIC's cloth manipulation algorithms; DLR's robotic hardware & control used in projects; KTH's soft fixture framework; RWTH's T7 concept for factory of the future.
Robotics/Automation Companies	Develop and supply robots, grippers, and integration services tailored to textiles	KUKA providing cobots & know-how in Robotextile project; Startup Sewts automating laundry handling; OmniGrasp commercializing electroadhesive gripper.
Textile/Apparel Manufacturers (SMEs & OEMs)	Act as testbeds and early adopters; provide domain expertise and requirements	Selmark hosting MERGING pilot (lingerie fabric handling); C&A investing in automated jeans plant with partners.
Recycling solution companies	Driving robotics and AI for circular textile value chains	NewRetex: AI/NIR sorting; Matoha: pocket NIR scanners; Resortecs: heat-soluble threads enabling robotic disassembly at 5× manual speed.
Industry Associations (EURATEX, Textile ETP)	Aggregate industry needs; lobby for support; facilitate partnerships and knowledge transfer	Co-leading EU Textile partnership; publishing reports on need for innovation; organizing brokerage events for project consortia.
Manufacturing Partnerships (EFFRA/Made in Europe, ADRA)	Roadmapping & ecosystem building; ensure RTM is included in broader manufacturing and AI/robotics agendas	Identified "flexible material handling" as a priority in SRIAs; clustering projects for shared learning.
National Agencies/ Clusters	Provide additional funding, pilot infrastructure, and local outreach to SMEs	German federal support for T7 and C&A FIT pilot; Portugal's textile cluster (CITEVE) running pilots on digital textile factories; regional funds for automation training (e.g., in Italy's Lombardy region).
Standard Bodies/ Regulators	(Emerging role) Develop safety and interoperability standards; adapt regulations to new tech	E.g., updating machinery directive guidelines for collaborative robots in textile factories (to ensure worker safety when robots handle sewing machines).

This matrix shows a **coordinated multi-level effort**. Europe's approach involves collaboration rather than silos. We see policy feeding research (through funding and strategy), research feeding industry (through prototypes and pilot demonstrations), and industry feeding back to both policy (through associations lobbying for enabling measures) and research (through practical feedback and requirements). This holistic network is a unique strength of Europe, as acknowledged in comparisons (next section). The challenge, however, is that consensus and joint projects take time – some critics say Europe is slower to commercialize because it spends much effort in coordination. The comparative analysis will delve into how this stacks up against the US's more entrepreneurial but fragmented approach and Asia's state-driven but fast-moving strategy.

In the next section, we compare Europe's strategy and progress with developments in the United States and Asia to put the EU's alignment in a global perspective. This will highlight where Europe leads and where it may be trailing, providing further context for evaluating overall alignment and formulating recommendations.

7 Comparative Analysis: Europe vs. US and Asia in RTM

Robot textile manipulation is a global challenge, and different regions have approached it in line with their industrial ecosystems and strategic priorities. In this section, we compare the EU's capabilities, drivers, and policy supports (as detailed above) with those of the United States and Asia (particularly China, and to some extent Japan and other nations). This comparative lens will illuminate competitive strengths and gaps.

7.1 United States: Startup-Driven Innovation and Public-Private Institutes

The United States does not have a centralized industrial policy akin to the EU's Horizon programs, but it has fostered innovation in RTM through a mix of **academic research, startups, and defense-funded initiatives**. In the rest of the section, this ecosystem is presented.

7.1.1 Advanced Robotics for Manufacturing (ARM) Institute

Founded in 2017 as part of the Manufacturing USA network, ARM (based in Pittsburgh) is a public-private consortium focused on lowering barriers for robotics in manufacturing. One of ARM's early priority areas was **apparel and textile** manufacturing, recognizing the large market and the fact that the US had largely offshored these jobs. Through competitive project calls, ARM funded several projects tackling pieces of the garment automation puzzle. For example:

- *"Robotic Assembly of Garments"* (sometimes dubbed *"Sewbo project" or "Bot Couture")*: This project, led by the startup **Sewbo** and collaborators, demonstrated an automated approach to sewing by laminating fabric with a water-soluble thermoplastic to make it temporarily rigid [2][1]. A robot (Universal Robots arm) could then handle these stiffened pieces and even sew them because they behaved like sheet metal. After sewing, the stiffener is washed out, leaving a normal garment. This is a clever materials-science-meets-robotics hack that garnered attention. It indeed *reshapes* the problem to fit existing robot capabilities. Europe's researchers watched this keenly; some have experimented with similar concepts (e.g., using starch sprays or freeze-sprays to stiffen fabrics during handling).
- *"Robotic Fabric Handling for Pick-and-Place"*: Another ARM project where the goal was to develop vision and gripping for picking up limp fabric pieces and placing them accurately [3]. This involved the company **SoftWear Automation** and others, focusing on automating the "kitting" process (preparing cut pieces for sewing).
- *"Semi-Autonomous Fabric Welding Workcell"* and *"3D Sewing of Shield"* – projects that looked at non-traditional garment assembly (like using welding for PPE or sewing 3D shapes for composite fabrics).

ARM's approach is very **applied and incremental**: rather than a single moonshot of a fully automated sewing line, they fund pieces that can modernize factories step by step. They require industry cost-share, so projects are closely tied to industry needs. The institute's director has emphasized that robotics and AI *"could be the key to reshoring this [apparel] industry" [101].*

7.1.2 Startups and Private Companies

The US's most prominent RTM startup has been **SoftWear Automation (Atlanta)**. SoftWear, spun out of Georgia Tech, developed a vision-guided robot workline called **Sewbot** that can sew basic garments like T-shirts with minimal human intervention. Their system uses multiple cameras and robotic clamps to continuously adjust fabric as it goes through a sewing head [94][98]. They made headlines around 2017 by partnering with a large Chinese apparel group (Tianyuan) to set up a Sewbot-powered T-shirt factory in Arkansas, aiming to produce millions of T-shirts for Adidas at near-China cost. While the ramp-up took longer than expected, SoftWear did reportedly achieve automated sewing of simple garments at high volume. By 2022, SoftWear was still refining the technology (they announced they would take orders for robots from that year). SoftWear also explored other products like **automated towel sewing** and **footwear upper stitching**. As of 2025, SoftWear has a significant investment, and its focus remains on commercializing these solutions at scale.

Other US companies:

- **Rethink Robotics** (before it closed) had demonstrated a garment handling demo with its Baxter robot, but that was rudimentary. In 2018, the assets of Rethink Robotics were bought by the German automation specialist HAHN Group. In 2021, Rethink Robotics joined the United Robotics Group GmbH, but ceased activity in 2024, to reappear again in the US with new products.
- **Siemens (US R&D arm)** has worked on sewing automation for automotive upholstery (some parallels to garment sewing).
- **Fashion for Good** (an international incubator with a base in the US) has nurtured startups like **Sewbo** and **Catalyst** (automated cutting/sewing for denim).

7.1.3 Academia

Top US universities (Carnegie Mellon, Berkeley, MIT, Cornell, etc.) have contributed heavily to the **science of deformable manipulation**. For instance, Berkeley's Robot Learning Lab did pioneering work on using deep learning and self-supervision to make a robot fold clothes from random piles (the "Laundry" project, around 2018). Carnegie Mellon's David Held co-authored a comprehensive survey on cloth manipulation [72], highlighting how US academics collaborate with Europeans (the survey had authors from CMU and European institutions). However, much US academic work is funded by general NSF or DARPA programs, not textile-specific calls. DARPA did have programs like *"Symbiotic Design for Assembly"* which included textile assembly in the scope (that program funded SoftWear's early dev via DARPA's former "Commerce" program).

7.1.4 Government Policy

Unlike the EU, the US does not have an explicit textile innovation policy with a sustainability bent. However, the Biden administration focused on manufacturing, including incentives for bringing jobs back. The **CHIPS and Science Act (2022)** and the Inflation Reduction Act don't directly address apparel, but they signify a climate where manufacturing and tech are supported. Some US lawmakers have indeed cited Sewbot as an example of tech that can revive jobs. On defense, the Pentagon's Defense Logistics Agency would like to source uniforms domestically (there are Berry Amendment requirements to source uniforms from the US), so they quietly support these automation efforts to ensure domestic capacity.

7.1.5 Comparison to EU

The US has some world-leading technology (Sewbo's concept, SoftWear's Sewbots) that arguably outpaced what any EU startup offered in the same period. However, the US approach relies on venture capital and specific consortia, and if those falter, there isn't a broad program to carry it through. Indeed, SoftWear's journey has been long (nearly a decade of R&D). The EU, by contrast, funded multiple parallel projects exploring various approaches (electroadhesion, dual-arm, AI learning). The EU might not have one single equivalent of a Sewbot system yet, but it has a portfolio of enabling tech and a network of stakeholders. Also, the EU's emphasis on human-friendly cobots is a bit different from SoftWear's approach of full automation for a dedicated product.

US strengths – entrepreneurial drive, direct industry investment (e.g., a Chinese company invested $20M+ in the Arkansas Sewbot factory), and focus on concrete ROI (the ARM projects always aim for a manufacturable solution).

US weaknesses – less cohesion, risk of fragmentation (if SoftWear or others fail commercially, the knowledge might not be shared widely as would be in EU projects), and less focus on sustainability (the push is more economic or defense-driven).

7.2 Asia: Scale, State Drive, and Continuous Improvements

Asia, especially **China**, is both the world's manufacturing hub for textiles and an increasingly important source of automation innovation. Key points:

7.2.1 China's Automation Boom

China's government has made automation a pillar of national strategy through *Made in China 2025* and subsequent initiatives [33]. The country leads the world in annual robot installations and is rapidly increasing its robot density. Initially, most robots went into electronics and automotive. Now, as labor costs rise and labor shortages emerge (yes, even in China, younger workers eschew sewing jobs), there's a push to automate sectors like apparel.

According to the South China Morning Post, large Chinese apparel manufacturers are indeed adopting more automation, from automated cutting to robotic palletizing of finished goods. **Esquel Group** (Hong Kong-based, the world's largest shirt maker) built a highly automated shirt factory to mitigate tariffs and rising costs [96]. They use automated guided vehicles, some robotic handling, and advanced IT systems (though they still employ many workers, each worker is more productive). China's **robotics companies**, e.g., SIASUN, HIT Robot Group, have developed some textile-focused robots (like automated sewing units for specific seams). There are trade fairs in China showcasing "sewbots", often by integrating existing sewing machines with robot arms for material handling.

A notable example: a Chinese company claimed to automate much of the T-shirt sewing process and aimed to produce millions of T-shirts for a major sports brand (this likely refers to Tianyuan's use of SoftWear's Sewbots, which ironically happened in the US, showing global interplay) [83]. Also, a video by CGTN (China state media) showed a "dark factory" for garments with automated systems making leggings with minimal lights on [14].

Critically, China's push is heavily state-supported with **subsidies** and local government incentives to factories to invest in robotics [105].

Robot density: As of 2023, China's robot density in manufacturing reached **470 robots per 10,000 employees**, surpassing the United States and Germany and ranking 3rd globally behind South Korea and Singapore [57]. The global average robot density also hit a record **162 robots per 10,000 workers**, more than doubling since 2016. However, in the textile sector specifically, robot density remains low worldwide due to the complexity of handling flexible materials. Even so, China likely leads textile automation experimentation, given its dominant share of global textile production and strong government support. According to the China Sewing Machinery Association, by 2025, a significant share of large garment factories in China plans to integrate intelligent sewing systems and robotic solutions for key processes [17]. This push is driven by state subsidies and local government incentives, such as tax breaks for factories investing in robotics.

7.2.2 Japan and South Korea

Japan historically attempted garment automation. In the 1980s, projects like a robot that could sew a shirt achieved some automation in factories making suits, using specialized machines and some robots. Today, Japan focuses on **service robots and industrial robotics** broadly; companies like JUKI and Brother (sewing machine makers) innovate incremental automation (like robotic arms to change sewing jigs) [47]. **South Korea**, with its super-high robot density, might lead in textile robotization too simply because it applies robots widely. But South Korea's apparel manufacturing is limited; they offshored to Vietnam largely. Interestingly, **Singapore** has high automation and a small fashion tech scene (the company Solomon in Singapore works on AI-guided sewing for shoes) [95].

7.2.3 Bangladesh, Vietnam, others

These countries dominate manual garment production. They have a vested interest in keeping labor costs low to maintain their edge. However, even there, wages are creeping up and labor unrest is a factor. Some larger factories (often owned by Hong Kong/Chinese companies) are introducing automation for quality inspection or material spreading. But widespread use of sewing robots is not yet visible; labor is still cheaper. There is some concern that if fully automated factories become viable, production could relocate back to consumer markets (which is exactly what EU and US are eyeing) – a potential economic threat to these countries. That's why organizations like the International Labour Organization study the impact of "sewbots" on developing economies.

7.2.4 Comparing Policy Approaches

China's approach is **top-down and target-driven**. They identify "smart manufacturing" model factories and invest heavily. For example, a city government might subsidize a "model textile factory" with 5G, IoT, and robots and showcase it. The EU approach is also top-down, but more consensus and research-heavy, with less direct subsidies for individual factories (except maybe through regional funds). The US approach relies more on market forces with some facilitation (ARM). In China, if the government decides textile automation is strategic, it can pour billions into it. The IFR data shows China's huge spending ($1.4B in robotics R&D by the government in 2023) [105]. So Europe must consider that while it debates and pilots, China could brute-force the problem with massive engineering manpower and money. However, it's not solely a money problem – it's a hard technical problem. Yet, Chinese universities (like Harbin Institute of Technology) and companies might crack some aspects sooner.

7.2.5 On Sustainability

Asia's focus is typically on efficiency and cost, though **China also pairs automation with energy efficiency** (the dark factory article noted a 1.7% drop in industrial energy use partly due to automation, aligning with carbon goals). But the driver is more "reduce reliance on labor, improve production". Social issues of job loss are emerging – sources mentioned projections of 12 million Chinese manufacturing jobs lost to robots by 2030 [105]. China is huge, so they might weather it by shifting labor to other sectors, but they have to manage potential unrest (there was a strike in Guangdong over robots replacing workers). Europe, conversely, is trying to save an industry that has already lost jobs, so the dynamic is different.

7.3 Europe vs Others – Key Differences

Europe's approach to RTM differs markedly from that of other global players, both in scope and strategic emphasis. While the European Union tends to embed RTM within a broader policy framework that includes sustainability, ethical labor standards, and regional cohesion, the United States frames RTM primarily through the lens of competitiveness and the re-shoring of manufacturing capacity. In contrast, China views RTM as a means of maintaining its dominance in global textile production while mitigating the pressures of rising domestic labor costs.

Collaboration is another key area where Europe diverges. European RTM initiatives often emerge from cross-border consortia that openly share findings and encourage alignment with broader EU goals such as interoperability and digital sovereignty. In the US, by contrast, innovation is more frequently driven by privately funded startups that guard trade secrets as part of their competitive edge. China, while increasing its academic output on cloth manipulation and frequently citing Western research, generally maintains a more insular approach in terms of technology development, favoring domestic applications over international technology transfer.

In matters of standardization and safety, the European Union tends to take the lead. It has actively shaped international norms—such as ISO standards for collaborative robots (cobots)—and is expected to play a similar role in defining protocols for safe human-robot collaboration on textile production lines. The United States typically relies on OSHA regulations, which may evolve to incorporate RTM-specific risks. China, meanwhile, often adopts ISO standards with a delay or develops domestic equivalents that may differ in scope or enforcement.

Commercialization trajectories also vary across regions. The United States has seen pioneering commercial efforts, most notably SoftWear Automation's Sewbots, which have made headlines for their ability to automate t-shirt assembly. Europe's commercial efforts remain more nascent; examples include Robotextile and some developments within Italian industrial automation firms, though these are less visible on the international stage. In Asia, RTM commercialization is more likely to be vertically integrated within large manufacturing conglomerates. For instance, a Chinese garment producer might develop RTM technologies in-house in collaboration with local integrators, rather than sourcing from third-party vendors. This model could foster fast deployment but risks generating vendor-specific solutions that are incompatible with international standards, leading to the emergence of competing ecosystems, such as SoftWear's Sewbots versus proprietary Chinese alternatives, each optimized for specific textile applications.

To illustrate comparative positioning, consider a scenario: automating a basic T-shirt sewing line. **SoftWear Automation (US)** has a solution undergoing trials. **China** might replicate that by licensing SoftWear's tech or developing a similar one at one of its research institutes. **Europe** doesn't have a ready product for that yet, but has pieces: the grippers from MERGING, the planning from academic labs, etc. Could Europe assemble these pieces into a home-grown T-shirt robot? Possibly, if some integrator did it, but it might require additional engineering that venture capital could drive if the market is seen as ripe. Alternatively, European garment makers might eventually just buy a solution from SoftWear or China if Europe doesn't produce one. This is a risk if the EU does not bridge that final gap.

In **policy terms**, Europe and the US are aligning in recognizing the strategic value of bringing tech to textiles. They even share knowledge –e.g., Global conferences, and likely SoftWear folks have talked to European firms (SoftWear's Series B had participation from the fashion industry, likely globally). China is racing to ensure it remains the production powerhouse, even if that means fewer workers and more robots.

One interesting note: According to IFR's 2024 report, China has now overtaken Germany in robot density, reaching 470 robots per 10,000 manufacturing workers in 2023 compared to Germany's 415, while South Korea and Singapore remain far ahead at the top of global rankings [57]. This highlights that Europe's manufacturing, heavily driven by the automotive sector, remains highly automated overall, but begins to lag behind. However, textiles represent only a small fraction of that automation. If we had a statistic representing textile lifecycle automation, Europe might still appear ahead on a relative basis, simply because it has so few textile factories and some pilot plants feature robotics. But in **absolute numbers**, China undoubtedly leads, given its vast textile industry and increasing deployment of robotics and AI in sorting, cutting, and assembly processes [17].

Finally, on **critical views**: Some in Asia might argue Europe's efforts are nice but irrelevant, as the center of gravity of production is in Asia, and they will adopt automation on their own terms. However, if Europe can perfect certain technology, it could sell it globally or at least use it to regain niche production.

In summary, **Europe's positioning** could be characterized as: *technologically strong in R&D, broad stakeholder engagement, forward-looking in tying to societal goals, but slower in commercial roll-out; reliant on public funding to de-risk early stages.*
US's positioning: *entrepreneurial, with some targeted funding, producing nearly market-ready solutions, but focusing on certain products and with less public visibility of results.*
China's positioning: *massive drive to automate motivated by economic strategy, potential to implement at scale quickly, but currently in process of moving from labor-driven to tech-driven production. Could catch up or surpass if they solve the tech, given their scale.*
This comparative view suggests that Europe cannot be complacent; it needs to accelerate turning its research advantage into deployed solutions to avoid falling behind commercially. At the same time, maintaining Europe's leadership in fundamental and applied research is equally crucial to ensure the continent remains at the forefront of innovation and can shape global standards in this field. Conversely, Europe's integrated approach (including policies on sustainability and worker training) might give it a *qualitative* edge—producing solutions that are safer, more flexible, and aligned with future "Industry 5.0" ideals, whereas others may focus purely on output and cost.

8 Challenges and Critical Perspectives

Despite clear progress and strong drivers for RTM in Europe, significant challenges and criticisms remain. This section evaluates the limitations of the data and evidence available, and presents opposing or skeptical viewpoints regarding the alignment of EU efforts with real needs and the economic feasibility of RTM. It essentially serves as a reality check: where are we falling short, what hurdles could derail the RTM momentum, and what do skeptics say that we need to consider?

8.1 Technical and Data Limitations

Technology Readiness vs. Hype: One fundamental challenge is the gap between prototypes and production-ready systems. Many achievements cited (robots folding laundry, picking fabric pieces, sewing simple seams, robots separating waste) are demonstrated under controlled conditions. There is often a **lack of comprehensive data** on performance in real factory settings. For instance, while MERGING's pilot at Selmark showed feasibility, how robust was it over time? How many hours could the cell run without human intervention or error? Such data is not always publicly available or might be underreported if issues occurred. This makes it hard to judge how close we are to "industrial grade" solutions. The academic literature can sometimes paint an optimistic picture, focusing on successes in trials, but not the fine details of failure rates or maintenance needs.

Benchmarks and Metrics: Until recently, there were no standard benchmarks to compare RTM solutions. Projects might report "we achieved 90% success in picking one layer of fabric", but the test conditions and definitions vary. It's crucial to critically evaluate results: e.g., a robot folded 90% of towels correctly in lab tests, but what about the 10% error rate? In a hotel laundry, 10% rework might be too high. The review by Longhini et al. 2024 points out the *underexplored area of benchmarking* in cloth manipulation [72]. Without common tasks and metrics, it's hard to quantitatively track progress. This is improving with things like the **Cloth Benchmarking** project or datasets like **DensePose-D (for garments)**, but still nascent. The absence of long-term field data (e.g., MTBF – mean time between failure for a fabric handling robot) is a limitation when persuading industry to invest.

Data on Adoption: It is difficult to quantify Europe's "RTM readiness" due to sparse data on automation adoption in textile factories. As mentioned, Europe doesn't have a centralized source tracking how many textile companies use robotics or AI. Official robotics statistics usually aggregate across industries and do not isolate textile applications. Trade associations have qualitative insights but not numbers. Anecdotal evidence suggests very low uptake of robotics in European apparel manufacturing to date (the few exceptions being pilot lines). The vast majority still rely on manual work or conventional automation (conveyor systems, etc.). This means there's little empirical evidence yet of productivity gains from RTM at scale. Such evidence is crucial to convincing more firms. It becomes a bit of a chicken-and-egg: no adoption -> no data on benefits -> skepticism remains -> no further adoption. Pilot projects need to break this cycle by transparently demonstrating ROI.

Edge Cases and Diversity: Textiles encompass a *huge variety* of materials (silk, denim, knit, woven, non-woven, etc.) and products (shirts, dresses, technical gear). A solution that works for one case might fail for another. Opponents argue that because fashion changes fast and products vary, fixed automation might always be behind the curve, and by the time you automate making last season's item, the designs change. The counterargument is that flexible robots could adapt. But that's yet to be proven widely, and more innovations are needed. This variety means enormous testing is needed. EU projects typically choose some representative cases (e.g., lingerie fabric, cables, etc.) but can't cover all. There's a risk that unknown failure modes lurk for other fabrics or processes.

8.2 Economic Feasibility and Business Case

High Costs and SME Constraints: Some experts question the economic viability of fully automating garment production, especially for low-margin, fast-fashion items. High up-front capital expenditure for robotics, combined with integration complexity, can deter SMEs that dominate Europe's textile industry. A sewing line in Bangladesh might have 100 workers costing, say, €100/month each – €10k/month. A fully robotized line might require €2 million capital investment plus maintenance. If one calculates net present cost, skeptics argue it's still cheaper to use cheap labor (at least in the short-to-mid term, especially for countries that have it in abundance). European SMEs often operate on thin margins, and investing in unproven tech is risky. Without clear business cases, adoption will lag. Automation in automotive succeeded because of high volume, low mix, and tolerance for capital expense, given high margins per car. Textiles are low margin per piece, and products change often.

There's also the risk of **stranded investments**, if technology changes fast, a system could become obsolete quickly. Or if consumer demand shifts (say to a different style of garment), a highly specialized automation line might not adapt.

Job Displacement and Social Resistance: Although Europe positions RTM as helping with a labor shortage, there is some social concern. Workers and trade unions in some countries might resist if they fear job losses. In Italy or Portugal, sewing jobs still exist; unions may call for retraining guarantees. The Just-Style article notes how AI/automation must be "human-centred" and involve the workforce in the transition [52]. If not handled well, there could be pushback or political hurdles. Some critics say, Why invest in saving an industry that inherently offers unpleasant jobs? They argue that perhaps those human resources should be shifted to other industries rather than trying to preserve textile manufacturing through robots. The EU emphasizes "no one left behind" in strategies, but tangible plans (like upskilling 50,000 textile workers to tech roles) must happen.

Cultural Acceptance: In the luxury sector, there's a cultural resistance to admitting any automation (they sell the image of handcraft). If automation increases, they might keep it secret to maintain brand mythos. This is fine, but it means they won't publicly champion robotics, which could slow diffusion because best practices aren't shared.

Realignment of Supply Chain: Automation alone doesn't solve all issues – moving production from Asia to Europe also implies rebuilding supply chains for fabric, trims, etc. Opponents of re-shoring say: Europe no longer has the ecosystem (many fabric mills closed or shifted focus). If you make clothes in Europe, you still import most fabrics from Asia, which reduces some resilience benefits. So a holistic approach is needed: otherwise, you might have a robot sewing line in Europe but waiting for fabric shipped from India, not much gain in independence or lead time. The EU textile strategy addresses some of this by promoting fiber and textile production in Europe, but that's a big challenge (cost of energy, environmental regulations, etc., are tougher in the EU for dyeing, for example).

Focus – Should the EU compete in apparel?: A strategic critical view: maybe Europe doesn't need to make basic clothes, even with robots. It might be wiser to focus on **technical textiles, medical textiles, and smart textiles** – areas where the EU already is strong and which are high value. Automating those might yield better ROI (for instance, automating production of carbon fiber composite fabrics for aerospace, or integrating electronics into textiles, etc., where cost tolerances are higher). Some experts from a purely economic angle might see chasing T-shirt or fast fashion production as chasing a bygone era, even with robots. They might propose that Europe's money is better spent on upskilling workers into design, branding, or very high-end artisanal work that cannot be automated, and leaving mass production (robotic or not) to others. However, such a stance might undervalue the benefits of distributed manufacturing and also ignore that technical advances in mass-market production often spill over to niche markets too.

Uncertain Timeline: Another critical perspective is the timeline of impact. Horizon Europe projects run till 2025-2026, and pilots might scale by 2030. But the socio-economic problems (labor shortage, etc.) are immediate. If robotic solutions take too long to mature, companies might not survive or might, by necessit,y outsource/offshore in the interim. For instance, if an Eastern European apparel maker can't find seamstresses today, they might close or move production, rather than wait five years for a robot solution. So there's a timing risk. The EU's processes (research->innovation->market) can be slow, and the private sector moves faster elsewhere. Critics point to how Speedfactory in Germany launched and closed in the time EU projects were still in planning phases; the industry moves quickly.

8.3 Policy and Priority Debates

Resource Allocation: Within EU circles, there might be debate about whether niche areas like RTM should get as much attention or funding. Robotics funding has many competing areas: healthcare robots, autonomous vehicles, etc. Why put money into making robots sew, when you could maybe use that money to advance AI or renewable energy tech? Proponents argue that textiles are a huge global market and the societal benefits (jobs, etc.) are worth it. It's telling that outside of the targeted FoF call, RTM isn't heavily present in many subsequent calls (e.g., the cluster calls are more generic or about AI). It could indicate some within the EU view it as an application that should be left to industry to solve if it's worth it, rather than continuously funding it with taxpayers' money. Nevertheless, the role of recycling automation and circular textiles is getting more attention in the policy agenda.

Focus on SMEs vs Large Co's: Some critique that EU projects often involve high-profile institutes and big companies, but might not sufficiently engage the small manufacturers who dominate the sector. The risk is developing solutions that are **too complex, specialized, or costly** to be adopted by SMEs. If the small cut-and-sew shop in Italy can't use it, the impact is limited. The Commission tries to involve SMEs (MERGING had SMEs like a lingerie maker, SoftManBot had an SME toy maker, etc.), but an ongoing challenge is ensuring tech trickles down. If not, there could be an alignment issue: capabilities built that are mismatched to user needs.

Environmental Footprint of Automation: A subtle point raised by some environmental critics: introducing robots and high-tech into the textile supply chain can increase energy use and electronic waste if not managed properly. If robots require energy from non-renewables, the carbon footprint might not actually be better than shipping goods by boat from a low-energy-cost country. Also, automated factories might encourage more consumption (since they can produce quickly and cheaply), which could counter sustainability goals. However, these points are speculative; studies would be needed to compare life-cycle impacts.

Feasibility of Full Automation: Some experts caution that *full* automation of sewn garment production is one of the toughest automation challenges and may not be solved in the near future. An often-cited quote in industry is "we can send a rover to Mars, but we can't fully automate a T-shirt". The reason is partly economic, it hasn't been worth the investment historically, and partly complexity. Some foresee a model where partial automation is the sweet spot: e.g., 50% of the work is automated, 50% still by humans, for flexibility and cost reasons. If that's the case, the narrative of lights-out factories might be overblown in the medium term. Instead, collaborative setups might dominate. Critics then say: if you still need workers (albeit fewer) and those are still hard to find in the EU, how much have you solved? The counter is that you'd need far fewer, and you can attract talent if jobs are more techy.

Opposing Visions within Industry: It's worth noting that some textile industry leaders remain cautious about embracing robotics as a core strategy. Some might invest more in **reshoring without automation**, using near-shore countries (Tunisia, Turkey) and lean manufacturing to be flexible. They might see automation as too risky or not mature and opt instead for other strategies (like investing in digital sales to reduce inventory, which also solves some waste issues, or adopting less labor-intensive manufacturing like 3D knitting, which doesn't require sewing). If large players go that route and succeed, it could deprioritize RTM. For example, Spanish giant Inditex (Zara) has kept a chunk of production in nearby countries with quick turnarounds using human labor. They might continue that and only use automation sparingly (maybe just in logistics, not sewing). So alignment is not universal; some brands might not see robotics as a must-have if they have alternative competitive models.

8.4 Critical Outcome Assessment

Policy Relevance: Some critics might ask: Is robot textile manipulation (RTM) truly a policy-relevant domain, or just a niche technical pursuit? At first glance, robotic sewing machines and fabric handling could seem trivial compared to grand challenges like climate change or AI sovereignty. However, advocates argue RTM links directly to **quality jobs, trade balance, and technological sovereignty**. Crucially, **RTM is broader than production automation**; it also encompasses **intramanufacturing handling** (e.g., moving, sorting, and quality-checking semi-finished goods) and **reverse logistics** for textiles. With the explosion of online commerce, millions of garments are returned each year and must be **sorted, inspected, and reintegrated into circular systems**, tasks that are labor-intensive today but could be streamlined through robotics and AI. Combined with **robotic recycling and disassembly technologies**, these advances align closely with the EU's **twin transition goals** (digital + green) and circular economy ambitions. The new **EU Textile Strategy and Textile Partnership** signals that the Commission considers RTM relevant within sustainable production and logistics systems [35]. Still, to secure long-term public funding, RTM initiatives must demonstrate real impact, **reducing waste, enabling reuse, and strengthening Europe's digital manufacturing leadership** beyond simply lowering production costs.

Feasibility of Economic Resurgence: A very critical economic historian might say: Europe lost the bulk of apparel manufacturing in the 1990s-2000s and it's not coming back in a major way. Automation will allow some localized production, but volumes will remain small compared to global production. Europe might more realistically aim for being a provider of technology to the world's manufacturers, rather than a manufacturer itself. If so, measuring success as "factories returning" might be the wrong metric. Instead, success could be European companies selling robotic solutions to Asian factories at scale. That would bring economic benefit (exporting high-tech equipment). Indeed, companies like France's Lectra do sell cutting machines globally. Perhaps the EU could focus on being the leader in high-tech textile machinery (as it historically was), updated for the robotics age, which is a valid path to competitiveness. Opponents of trying to bring factories back might favor this, as it plays to the EU's strength in engineering over low-cost production.

However, the *strategic autonomy* argument counters that some local capacity is needed (like for PPE during a crisis, as painfully learned in 2020). So maybe a balanced view is necessary.

In summary, the critical perspectives highlight that while Europe is pushing RTM, success is not guaranteed nor universally agreed upon. The alignment of capabilities, drivers, and policies has potential misalignments: technology might not be ready for the most urgent needs, the economics might not yet favor rapid adoption, and some stakeholders remain unconvinced. These criticisms are important to consider to adjust strategies. Many of the recommendations (next section) address exactly these concerns (e.g., de-risking investment, focusing on collaborative robots to ease adoption, etc.).
Ultimately, the question of *policy relevance or economic feasibility* boils down to timing and execution: can Europe turn RTM into a practically viable and widely beneficial endeavor soon enough? If it can demonstrate success stories –say, a half-dozen automated micro-factories profitably operating in Europe by 2025–2030- it will validate the effort. If not, skeptics will say the resources could have been better spent elsewhere. This report leans toward optimism that with the right measures, Europe can make RTM a pillar of a renewed, advanced **manufacturing, logistic and recycling sectors** – but the challenges outlined here must be explicitly tackled.

9 Policy and Investment Recommendations

In light of the analysis above, covering Europe's capabilities, socio-economic drivers, comparative position, and challenges, we now present a set of forward-looking recommendations. These aim to strengthen Europe's strategic positioning in robot textile manipulation, ensuring that current efforts translate into tangible industrial and societal gains. The recommendations are crafted for policymakers at the EU and national levels, research funding agencies, and industry alliances, aligning with Horizon Europe's trajectory and beyond.

1. **Establish Public-Private "EU Textile Automation Hubs":** Create regional innovation hubs or competence centers focused on RTM, and map the ecosystem. The Network of Excellence proposed in the ROMANDIC EU project is a step in this direction. In these facilities, industry (especially SMEs) can access state-of-the-art equipment, expertise, and training. These hubs would serve as *pilot factories* and testbeds – for example, one hub could host a flexible robotic sewing line that local companies can experiment with (perhaps on a rental or project basis). The hubs should be co-funded by the EU (via Digital Europe Programme or ERDF) and industry, and connected in a network to share learnings. Similar to existing Digital Innovation Hubs but specialized, they should have demonstration facilities for different sub-tasks (automated cutting, automated stitching of certain garments, intrafactory handling, inverse logistics, etc.). This directly addresses the **gap between lab and industry** by providing a low-risk environment for companies to try automation [52]. It also builds local capacity: a hub in a traditional textile region (e.g., Portugal's Norte, Italy's Tuscany, Romania's Bucharest region) can help reskill workers and attract tech providers to those areas, creating an ecosystem. The hubs can collaborate with the new **Textiles European Partnership** to align with its agenda [35]. A key aspect is including *application engineers* and *technology brokers* who help tailor solutions to SME needs, effectively translating research output to shop-floor applications.

2. **2. Incentivize Early Adoption through Financial Instruments:** To overcome the high initial investment barrier for automation, the EU and EIB (European Investment Bank) should set up targeted financing schemes. For instance, a **European Textile Automation Fund** could provide low-interest loans or leasing options for purchasing robotic equipment for textile manufacturing, with lighter terms for SMEs or first-of-a-kind implementations. Additionally, under Horizon Europe or national programs, consider a *"voucher"* system where SMEs get grants to access the above-mentioned hubs or to hire integrators to pilot automation in their facilities (similar to vouchers in I4MS programs earlier). The idea is to reduce risk for pioneers and create successful examples. Tax incentives at the national level could also help (e.g., accelerated depreciation for automation equipment, as some countries did under Industry 4.0 plans). These measures should be tied to measurable outcomes (jobs safeguarded, production brought back, etc.) to satisfy socio-economic criteria. The **goal is to make the business case positive** for companies that are on the fence due to cost.

3. **Prioritize Modular, Upgradeable Solutions in R&D Calls:** Future research calls (Horizon Europe 2025-27 and beyond) should emphasize **modularity and flexibility** of RTM systems. This means funding projects that develop automation components that can be easily reconfigured for different products or integrated into existing production/handling/recycling lines. For example, a robotic cell that can switch from sewing

T-shirts to sewing masks with minimal changes, or a vision system that can be trained quickly on new waste patterns. By focusing on modularity, the EU caters to the reality of fast-changing fashion cycles and SME needs for versatile equipment. This could be implemented by making it a criterion in proposal evaluations that solutions address multi-use or quick changeovers. It also encourages the development of **standards** (interface standards for robots to talk to sewing machines, etc.), which the EU can spearhead. A concrete action: commission a **standards roadmap** via CEN/CENELEC for "Robots in Textile Lifecycle" to identify what standards (safety, interoperability) are needed and fund projects to develop those. Standardization will reduce integration costs, an important factor for SMEs.

4. **Integrate Sustainability Goals Explicitly into RTM Projects:** To align with Europe's Green Deal and circular economy ambitions, any push for automation should also drive environmental gains. EU projects and industry initiatives should therefore explicitly incorporate sustainability targets. For instance, automated processes should aim to minimize material waste (perhaps cameras detect fabric defects and optimize cutting to avoid waste patches) and energy use (maybe by intelligent power management or using renewable energy on-site). Projects that combine **recycling with automation** – e.g., robots that can sort textile waste for recycling or disassemble garments – should be promoted under both textile and robotics funding lines. This ensures RTM supports the EU Strategy for Sustainable Textiles [41][40]. Also, life-cycle assessments (LCA) should be conducted for new automated production vs. conventional production to quantify benefits or reveal areas to improve. If results show significant carbon or waste reduction, that can be used to create consumer-facing narratives (like labels saying "This product was made in an EU smart factory with X% less waste and Y% lower carbon footprint"). Such narratives can increase market demand for EU-made sustainable products, reinforcing the economic logic for RTM.

5. **Expand Skills Development and Transition Programs:** A successful transition to automated textile manufacturing requires a workforce with new skills (robot operators, maintenance techs, AI quality control analysts, etc.). Building on initiatives like the **TCLF Skills Alliance [39]**, the EU should fund specialized courses, apprenticeships, and on-the-job training programs focusing on *textile automation*. This could involve updating curricula at textile vocational schools to include robotics and digital skills, and conversely, including textile materials basics in robotics/mechatronics courses. Funds from the Just Transition Fund or ESF+ (European Social Fund) could be allocated for retraining workers from roles being phased out (e.g., conventional sewing operators) into new roles (robotic cell supervisors or technicians). Furthermore, encourage knowledge exchange: maybe experienced automotive automation technicians could be cross-trained to work in textile manufacturing or recycling factories – initiatives that break down sector silos in the labor force. Ensuring the current workforce is not left behind will also help mitigate social resistance (workers see a path for themselves in the new era, not a dead end). An example action: create a **"EuroTextile Tech Academy"** that offers intensive short courses across Europe (perhaps at the hubs proposed) for SME owners, engineers, and workers to get hands-on with RTM technologies and learn how to implement them.

6. **Foster International Collaboration selectively while protecting European IP:** Europe should continue to observe and collaborate on RTM globally, but also carefully

manage intellectual property and competitive advantages. This means encouraging European researchers and companies to engage in international forums (ISO, IEEE, conferences) to lead standard-setting and showcase leadership, *but* also taking measures to help European innovations reach market before or at least alongside foreign ones. Perhaps the EU can support patenting costs or commercialization support for promising outputs from projects (to avoid them languishing in reports while non-EU actors scoop the idea). On collaboration: perhaps a transatlantic workshop between the EU's Textile Partnership and the US ARM Institute could be organized, to share best practices and avoid reinventing the wheel on tough challenges (like discussing SoftWear's lessons vs. EU projects' lessons). With Asia, engagement could be through international bodies or bilateral research on standards, but Europe should ensure its companies can compete. One idea: the EU could initiate a **UNIDO[2] or ILO[3]-backed program** to introduce safe and fair automation in developing country textile factories, with European tech – positioning Europe as a provider of advanced solutions that also improve worker conditions globally. This could create a market for EU RTM tech beyond Europe and reinforce the idea that automation and good jobs can go hand in hand (potentially easing global inequalities and avoiding a backlash that robots are stealing jobs in poorer nations). It's a delicate balance, but strategic international cooperation can accelerate development while maintaining Europe's values focus (e.g., ethical AI in fashion).

7. **Support Niche Markets and Quick Wins:** To build momentum, EU and national initiatives should also aim for some quick wins in niches where RTM can deliver immediate value. For example, **personal protective equipment (PPE)** (like masks, gowns), as seen in the EU project SoftEnable healthcare use-case, could be a target for rapid automation because of its strategic nature and relatively standardized designs. The EU could fund a challenge to design a fully automated mask production cell (some exist since COVID, but improving them and ensuring EU supply). *Recycling*, the focus of the recently started EU project FlexCycle, is one of the markets with the most expansion and impact in the EU. Another niche: **customized sportswear or medical textiles** (like compression garments, which can be made on-demand with body scanning and automated cutting/sewing). If a few highly visible products can be made end-to-end in Europe with robots (and perhaps even at competitive cost), it showcases the potential to the broader industry. These niches often have higher margins, which can better absorb initial costs. They act as beachheads for wider adoption.

8. **Continuously Involve End-Users in R&D:** A sometimes-cited issue is that tech developers may be far removed from actual factory realities. To keep alignment, future R&D projects should have *strong end-user involvement* from day one – not just as advisory board members, but co-creating solutions. Perhaps adopt a "living lab" methodology: for instance, set up experimental production lines within existing factories (with real products, real timelines) as part of the research. This was done to some extent (e.g., MERGING's cell in a real factory, C&A's pilot involvement), and it should become standard practice. Policymakers can encourage this by requiring testbeds in proposals or funding two-phase projects (Phase 1 lab development, Phase 2 in-factory trial). This

[2] United Nations Industrial Development Organization
[3] International Labour Organization

grounds innovations in practicality and also helps convert conservative industry folks when they see it working in an environment they recognize.

9. **Address Societal Concerns Proactively:** The EU should accompany the technological push with awareness campaigns and dialogue about the future of work in the textile industry. This includes transparently communicating that some jobs will change, but highlighting the opportunities for better quality jobs and the plan for reskilling. Perhaps under the **European Social Dialogue** in the textile sector, start discussions on how to ensure a just transition for workers with automation. Having union buy-in via, say, an agreement that no one willing to upskill will be left unemployed without support, could ease tensions. Additionally, highlight the **improvement of working conditions** that automation can bring – e.g., robots can eliminate repetitive strain injuries from tasks like manual cutting or reduce exposure to dust in material or waste handling. This narrative ensures broader societal alignment and avoids backlash.

10. **Monitor and Adjust Strategy Continuously:** Finally, given the dynamic global context, the EU should maintain a mechanism to monitor progress in RTM and adjust policies. Perhaps the Textile Partnership can include a working group that annually reviews technological progress (maybe using KPIs like number of factories adopting, performance metrics of new tech, etc.) [35]. If they find adoption slow, they could recommend new interventions (maybe standardizing more, or even protectionist measures if needed to nurture a nascent EU automation industry). Conversely, if breakthroughs occur (like someone cracks fully automated sewing of complex garments), the EU should be ready to support rapid scale-up of that innovation in Europe, so we don't lose the edge.

In conclusion, these recommendations form a multi-faceted plan: building infrastructure (hubs), easing financial barriers, focusing R&D where it counts (flexibility, standards, sustainability), ensuring people are prepared and onboard, and keeping an eye on the global race. By implementing such measures, the EU can significantly **strengthen alignment** between its capabilities and the evolving needs in RTM. The aim is that by the end of this decade, Europe will have a critical mass of semi-automated textile production, handling and recycling that is economically viable, sustainable, and provides high-quality employment, thus realizing the vision of a competitive, innovative, and resilient European textile industry empowered by robotics.

10 Conclusion

Europe's pursuit of robot textile manipulation sits at the intersection of technological innovation, economic strategy, and social imperative. Over the past ten years, and especially since 2020, the European Union has marshaled notable scientific prowess and policy support towards overcoming the age-old challenge of automating the handling and fabrication of textiles – a domain once thought too complex for machines. This comprehensive assessment finds that **Europe has made substantial strides in aligning its R&D capabilities and policy frameworks with the industrial needs in RTM**, though gaps remain to be bridged.

On the capability front, European researchers and companies have delivered innovations that push the state-of-the-art: from electroadhesive grippers that can gently lift flimsy fabrics, to dual-arm robot setups that coordinate like skilled tailors, to AI algorithms that enable a robot to "see and feel" a garment's properties and adapt accordingly. Horizon Europe's focus and funding, building on Horizon 2020's foundation, have ensured that Europe is at the cutting edge of these technologies. The formation of networks (e.g., ROMANDIC's Network of Excellence) and partnerships (Textiles European Partnership) demonstrates foresight in consolidating knowledge and aligning stakeholders – a uniquely European approach to collaborative innovation.

Socio-economically, Europe's needs are clear and pressing. The analysis presented shows a confluence of drivers –an aging workforce leaving critical skill gaps, rising demand for faster and sustainable local production, and vulnerabilities in over-globalized supply chains– all of which RTM can help address. The **labor shortage** in apparel manufacturing in Europe is real and documented, and robots offer a way to not only fill this gap but also to transform these jobs into higher-skilled, more attractive roles. **Sustainability** has become a non-negotiable goal for Europe, and the report outlined how automation can contribute to greener textiles (through waste reduction, on-demand production, and enabling recycling processes). This tight linking of RTM to sustainability and resilience goals means Europe's pursuit is not a tech quest in isolation but part of a broader industrial renewal aligned with European values.

Comparatively, Europe does not operate in a vacuum –the United States and Asia are charting their paths. The US, via startup dynamism and institutions like ARM, has produced near-market solutions (like Sewbots) that Europe must match or collaborate with to stay competitive. Asia, particularly China, is accelerating automation on an unprecedented scale, backed by heavy investment and a drive for technological self-reliance. In this race, Europe's advantage lies in its *holistic perspective*: it is not just automating for cost, but for **quality, sustainability, and human-centric production**. If Europe can execute its strategy effectively, it could lead in high-tech, ethical textile manufacturing – carving out a niche distinct from mass, purely cost-driven production. The recommendations put forth aim to ensure that Europe's innovation doesn't stay in labs but translates to factory floors, and that Europe's ethical and environmental standards become part of the competitive edge of its automated manufacturing.

The challenges are non-trivial. Technical hurdles in handling deformable materials are still being overcome, and economic viability for SMEs remains a concern raised by many. This report has not glossed over these issues; rather, it has identified them and proposed measures to mitigate them (from financial incentives to skills training and modular design). Opposing views that question the policy relevance of RTM or doubt its feasibility in the near term have been considered. Ultimately, the evidence gathered suggests that while full automation of garment production is indeed challenging, *partial automation and smart augmentation* of human work are within reach and can deliver substantial benefits. Europe's policies, such as support for collaborative robots and worker retraining, are wisely tailored to this realistic trajectory of incremental automation adoption rather than an overnight revolution.

In conclusion, we return to the central question: **How aligned are Europe's current capabilities, drivers, and policies with the evolving needs in robot textile manipulation?** The findings indicate a strong alignment on intent and a growing alignment on capacity. The EU has recognized the evolving needs – for agility, sustainability, and onshore production – and has launched initiatives targeting them. European capabilities developed through research are impressive and, in some niches, world-leading. Policies and funding mechanisms, from Horizon Europe calls to the new Textile Partnership, need to be in place to continue the momentum. To complete the alignment, Europe now needs to focus on implementation and scale-up, ensuring that what has been developed in theory and prototypes finds its way into widespread practice.

If the recommended actions are pursued, the coming years could witness Europe solidifying a new paradigm in textiles: **one where robots and humans work side by side to produce textiles efficiently, sustainably, and competitively on European soil**. Such a scenario would have profound positive implications – it would mean a revitalized European textile industry less dependent on distant labor pools, a workforce engaged in safer and higher-skilled jobs, and consumers enjoying innovative products that are ethically and sustainably made. Europe would also strengthen its technological sovereignty by mastering a complex automation frontier, which could spin off into other industries dealing with flexible materials (food, agriculture, etc.). Moreover, Europe could export this know-how to upgrade industries globally, exemplifying leadership in responsible innovation.

In essence, Europe stands at a pivotal moment: armed with cutting-edge RTM technologies and driven by clear socio-economic imperatives, it has the opportunity to turn the long-held dream of automated textile manufacturing into a reality that underpins economic resilience and growth. The task now is to proceed with determination, investment, and inclusive planning to realize this vision. By doing so, Europe will not only address its own needs but also set a model for how to integrate advanced automation into traditional industries in a human-centric and sustainable way – truly embodying the spirit of a modern "Industrial Renaissance". The threads of policy, technology, and societal goals are coming together; with careful weaving, Europe can indeed stitch a successful future for robot textile manipulation.

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